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ABSTRACT

The history of the National Aeronautics and Space Administration Skylab program is provided in this three-part book. Part I (chapters 1 to 5) traces the origins of the Skylab concept from its emergence in the period 1962-65 through its evolution into final form in 1969. Part II (chapters 6 to 13) focuses on the period from 1969-73, considering the development of the spacecraft modules, the experiments they carried, and the preparations to launch and operate them. Chapter 6 focuses on the program leaders, the problems they faced, and the tools they used to manage Skylab. Chapters 7 through 11 deal with the major experimental programs and the spacecraft components. Houston's preparations for directing the missions and the launching of Skylab are treated in chapters 12 and 13 respectively. Part III (chapters 14 to 19) deals with the Skylab launch accident (the meteoroid shield ripped away, leaving the workshop exposed to solar heat and disabling its solar panels), Skylab missions, program results (including medical and solar/earth observation findings), and the end of Skylab. A summary of missions, list of major contractors, list of experiments, and additional documentation are included in appendices. (JN)

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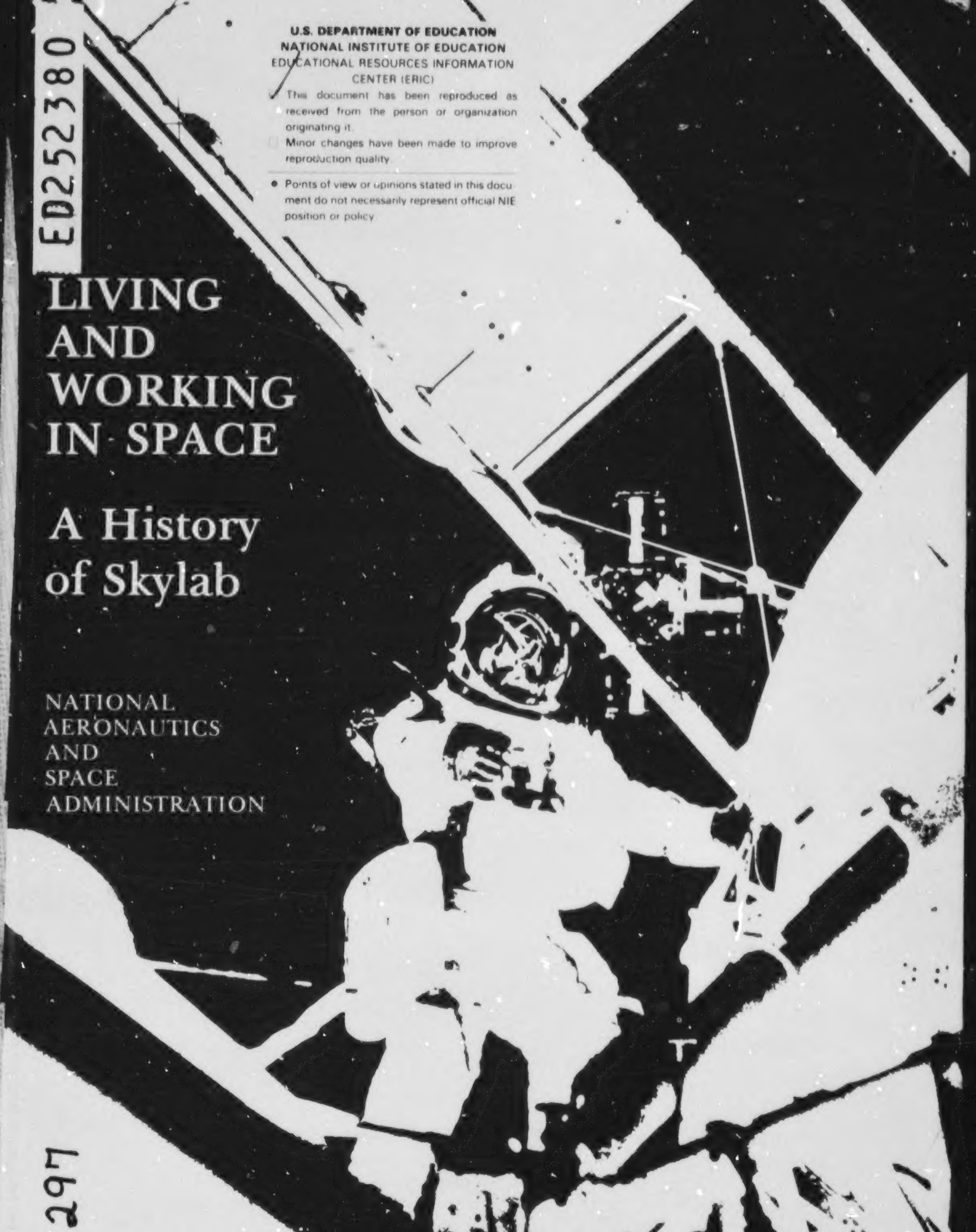
LIVING AND WORKING IN SPACE

A History of Skylab



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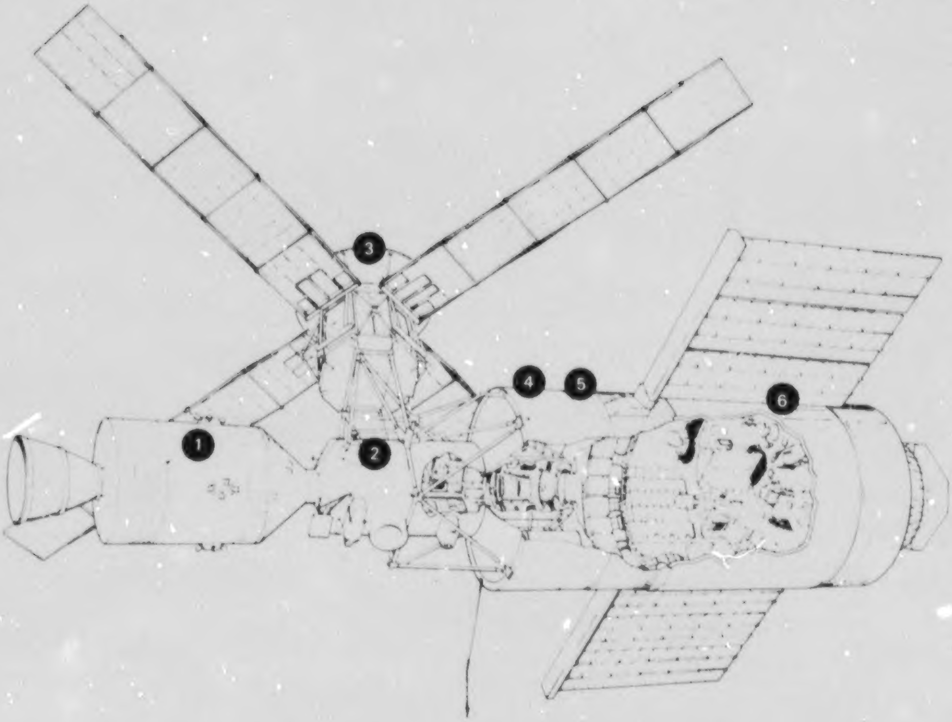

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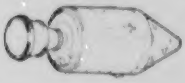
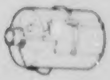
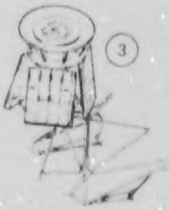
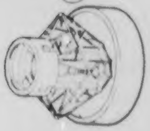
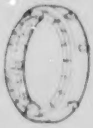
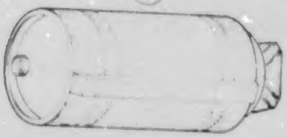
① 	Apollo Command and Service Module	Crew Ascent & Descent	10.5	3.9	10.4
② 	Multiple Docking Adapter	Docking Telescope & Earth-Resource Controls & Displays	5.3	3.1	32.3
③ 	Apollo Telescope Mount	Solar Observation	4.1	—	—
④ 	Airlock Module & Fixed Shroud	Power Control & Distribution Environmental Control Utility Center Data System Extravehicular Activity Port	5.4	3.1	17.3
⑤ 	Instrument Unit	Launch Vehicle Control	0.9	6.6	—
⑥ 	Orbital Workshop	Primary Living & Working Area Experiment Laboratory Stowage	14.7	6.6	270.2

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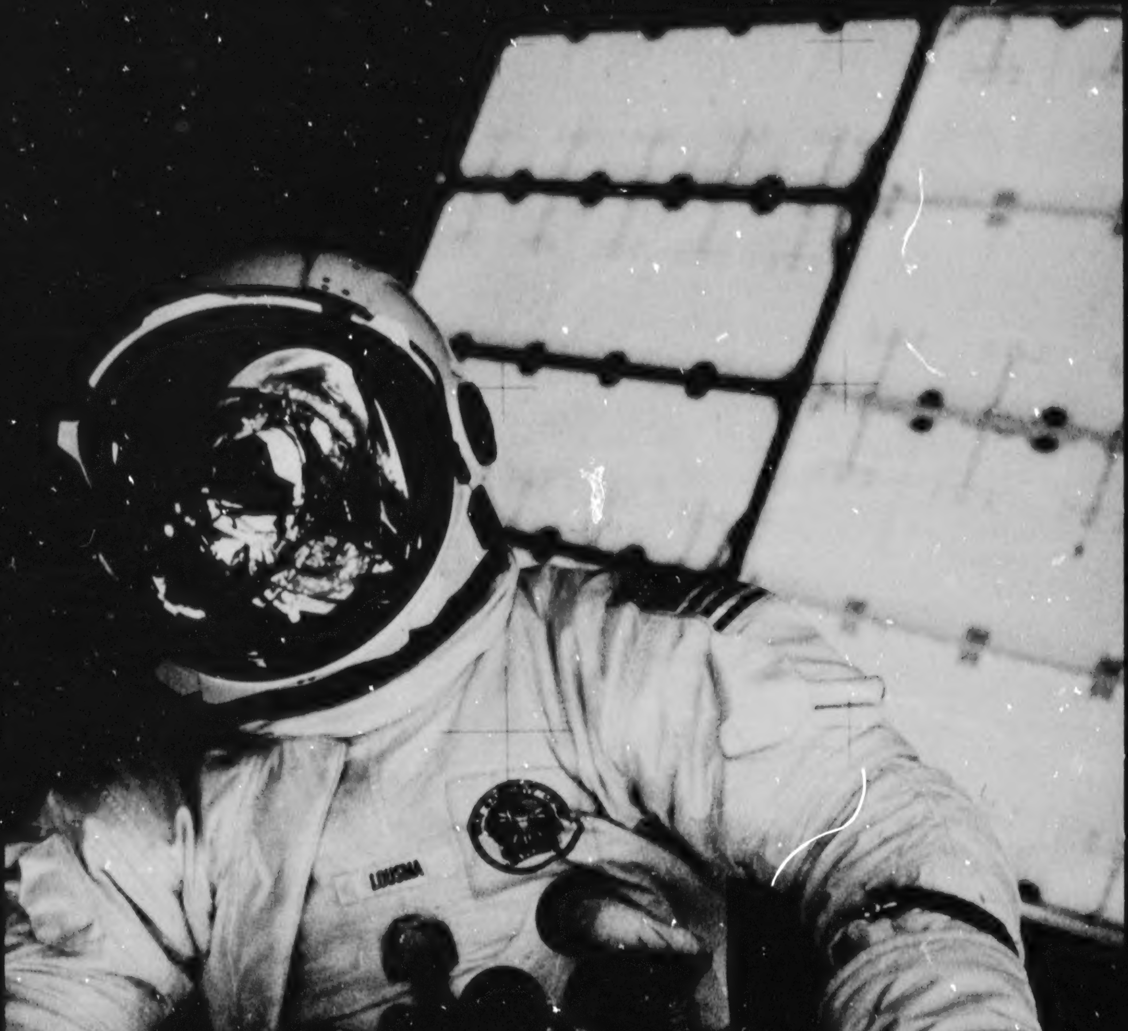
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LIVING AND WORKING IN SPACE

A History of Skylab

W. David Compton
and
Charles D. Benson

The NASA History Series

Scientific and Technical Information Branch 1983
National Aeronautics and Space Administration
Washington, DC

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NASA maintains an internal history program for two principal reasons. (1) Publication of official histories is one way in which NASA responds to the provision of the National Aeronautics and Space Act of 1958 that requires NASA to "provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof." (2) Thoughtful study of NASA history can help managers accomplish the missions assigned to the agency. Understanding NASA's past aids in understanding its present situation and illuminates possible future directions.

One advantage of working on contemporary history is access to participants. During the research phase, the authors conducted numerous interviews. Subsequently they submitted parts of the manuscript to persons who had participated in or closely observed the events described. Readers were asked to point out errors of fact and questionable interpretations and to provide supporting evidence. The authors then made such changes as they believed justified. The opinions and conclusions set forth in this book are those of the authors; no official of the agency necessarily endorses those opinions or conclusions.

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Preface

The program that became Skylab was conceived in 1963, when the Office of Manned Space Flight began to study options for manned programs to follow Apollo. Although America's lunar landing program was a long way from successful completion, it was not too soon to consider what should come next. The long lead times required for space projects dictated an early start in planning if manned spaceflight was to continue without a momentum-sapping hiatus.

The circumstances in which this planning was conducted in 1963–1967 were not auspicious. A consensus seemed to exist that earth-orbital operations offered the most promise for "exploiting the investment in Apollo hardware"—a favorite justification for post-Apollo programs. But firm commitment and support were less evident. A minority opinion—strongly expressed—condemned the lunar landing as an expensive and unnecessary stunt. NASA's budget requests were rigorously scrutinized and had to be justified as never before. To compound the space agency's problems, the Air Force embarked on a program that seemed to duplicate OMSF's proposals. And NASA's policy-makers seemed to be waiting for a mandate from the country before proceeding with post-Apollo programs.

Nonetheless, OMSF went ahead, developing both general plans and a specific idea for manned earth-orbital operations. In 1965 the Apollo Applications Program office was opened to oversee programs using the impressive capability developed for the lunar landing to produce results useful to clients outside the aerospace complex. Initial plans were grandiose; under the pressures generated by the completion of Apollo, they yielded until by 1969 a bare-bones, three-mission program remained.

Part I of the present volume details the background against which post-Apollo planning was conducted—the cross-currents of congressional doubt, public opposition, and internal uncertainty that buffeted Apollo Applications from 1963 to mid-1969. When *Apollo 11* returned safely, Apollo Applications—or Skylab, as it was soon renamed—emerged as a program in its own right, successor to Apollo, which would lay a foundation for manned spaceflight for the rest of the century.

Although it used Apollo hardware and facilities, Skylab's resemblance to the lunar-landing program ended there; and in part II we examine how Apollo components were modified for earth-orbital operations. The modification of existing spacecraft, the manufacture and checkout of new modules, the design of experiments for science and applications, and the changes in astronaut training, flight control, launch operations, and inflight operations that had to be made, all created new problems. Coordination among NASA Headquarters, the field centers, experimenters, and contractors may have been more complex than it had been in Apollo, and program management as a crucial part of the program is discussed in part II.

Part III chronicles the missions and examines the program's results. An accident during launch of the workshop very nearly killed Skylab aborning, and saving the program called for an extemporaneous effort by NASA and its contractors that was matched, perhaps, only by the effort that saved *Apollo 13.* That done, the three manned missions set new records for sustained orbital flight and for scientific and technological productivity. A preliminary assessment of the results from Skylab and a chapter on the last days of the spacecraft conclude part III.

Treatment of a program having as many different components and objectives as Skylab required a distinct division of labor between the authors. Generally, Charles Benson wrote the chapters dealing with program organization and management, congressional and budgetary matters, astronaut training, and launch operations. David Compton was responsible for the chapters dealing with the background to science in the manned spaceflight program, the science projects, the development and testing of flight hardware, the results, and the workshop's reentry. Each of us wrote part of the mission operations story: Benson the chapters on launch, the accident and repair, and the first two manned missions, Compton the chapter on the third mission. The principal joint effort is chapter 1, to which we both contributed and which both of us revised.

A word on coverage is in order. While we believe our story is complete through the end of the manned missions, we acknowledge that coverage of the program's results is not. This resulted from time limitations as much as anything else; our contracts expired before most of the results were available. In view of this, the appearance of a chapter on *Skylab*'s demise may seem strange. It is included because while the manuscript was being reviewed and prepared for publication, *Skylab* became an object of worldwide interest as it headed for reentry. This seemed to require completion of the operational story.

Our debt to Skylab participants is great. No one we approached, in NASA or its aerospace contractors, was anything but helpful. They gave us their time for personal interviews, assisted us in locating documents, and took the time to review draft chapters and offer critical comments. NASA history personnel at Headquarters, at Johnson Space Center, and at Kennedy Space Center (Marshall Space Flight Center had no history office by the time we undertook this work) were equally helpful. Without the help of all these people our task would have been much harder, and if we do not single out individuals for special recognition it is because all deserve it. Responsibility for the story told in this book, of course, is our own, and any errors that remain are ours as well.

W. D. C.
C. D. B.
November 1981

Part I

From Concept through Decision, 1962–1969

An earth-orbiting station, equipped to study the sun, the stars, and the earth, is a concept found in the earliest speculation about space travel. During the formative years of the United States space program, space stations were among many projects considered. But after the national decision in 1961 to send men to the moon, space stations were relegated to the background.

Project Apollo was a firm commitment for the 1960s, but beyond that the prospects for space exploration were not clear. As the first half of the decade ended, new social and political forces raised serious questions about the nation's priorities and brought the space program under pressure. At the same time, those responsible for America's space capability saw the need to look beyond Apollo for projects that would preserve the country's leadership in space. The time was not propitious for such a search, for the national mood that had sustained the space program was changing.

In the summer of 1965, the office that became the Skylab program office was established in NASA Headquarters, and the project that evolved into Skylab was formally chartered as a conceptual design study. During the years 1965–1969 the form of the spacecraft and the content of the program were worked out. As long as the Apollo goal remained to be achieved, Skylab was a stepchild of manned spaceflight, achieving status only with the first lunar landing. When it became clear that America's space program could not continue at the level of urgency and priority that Apollo had enjoyed, Skylab became the means of sustaining manned spaceflight while the next generation of hardware and missions developed.

The first five chapters of this book trace the origins of the Skylab concept from its emergence in the period 1962–1965 through its evolution into final form in 1969.

1

What to Do for an Encore: Post-Apollo Plans

The summer of 1965 was an eventful one for the thousands of people involved in the American space program. In its seventh year, the National Aeronautics and Space Administration (NASA) was hard at work on the Gemini program, its second series of earth-orbiting manned missions. Mercury had concluded on 16 May 1963. For 22 months after that, while the two-man Gemini spacecraft was brought to flight readiness, no American went into space. Two unmanned test flights preceded the first manned Gemini mission, launched on 23 March 1965.[1]

Mercury had been used to learn the fundamentals of manned spaceflight. Even before the first Mercury astronaut orbited the earth, President John F. Kennedy had set NASA its major task: to send a man to the moon and bring him back safely by 1970. Much had to be learned before that could be done—not to mention the rockets, ground support facilities, and launch complexes that had to be built and tested—and Gemini was part of the training program. Rendezvous—bringing two spacecraft together in orbit—was a part of that program; another was a determination of man's ability to survive and function in the weightlessness of spaceflight.

That summer the American public was getting acquainted, by way of network television, with the site where most of the Gemini action was taking place—the Manned Spacecraft Center (MSC). Located on the flat Texas coastal plain 30 kilometers southeast of downtown Houston—close enough to be claimed by that city and given to it by the media—MSC was NASA's newest field center, and Gemini was the first program managed there. Mercury had been planned and conducted by the Space Task Group, located at Langley Research Center, Hampton, Virginia. Creation of the new Manned Spacecraft Center, to be staffed initially by members of the Space Task Group, was announced in 1961; by the middle of 1962 its personnel had been moved to temporary quarters in Houston; and in 1964 it occupied its new home. The 4.1-square-kilometer center provided facilities for spacecraft design and testing, crew training, and flight operations or mission control. By 1965 nearly 5000 civil servants and about twice that many aerospace-contractor employees were working at the Texas site.[2]

Heading this second largest of NASA's manned spaceflight centers was the man who had formed its predecessor group in 1958, Robert R. Gilruth. Gilruth had joined the staff at Langley in 1937 when it was a center for aeronautics research of NASA's precursor, the National Advisory Committee for Aeronautics (NACA). He soon demonstrated his ability in Langley's Flight Research Division, working with test pilots in quantifying the characteristics that make a satisfactory airplane. Progressing to transonic and supersonic flight research, Gilruth came naturally to the problems of guided missiles. In 1945 he was put in charge of the Pilotless Aircraft Research Division at Wallops Island, Virginia, where one problem to be solved was that of bringing a missile back through the atmosphere intact. When the decision was made in 1958 to give the new national space agency the job of putting a man into earth orbit, Gilruth and several of his Wallops Island colleagues moved to the Space Task Group, a new organization charged with designing the spacecraft to do that job.[3]

The Space Task Group had, in fact, already claimed that task for itself, and it went at the problem in typical NACA fashion. NACA had been a design, research, and testing organization, accustomed to working with aircraft builders but doing no fabrication work itself. The same mode characterized MSC. The Mercury and Gemini spacecraft owed their basic design to Gilruth's engineers, who supervised construction by the McDonnell Aircraft Company of St. Louis and helped test the finished hardware.[4]

In the summer of 1965 the Manned Spacecraft Center was up to its ears in work. By the middle of June two manned Gemini missions had been flown and a third was in preparation. Thirty-three astronauts, including the first six selected as scientist-astronauts,* were in various stages of training and preparation for flight. Reflecting the general bullishness of the manned space program, NASA announced plans in September to recruit still more flight crews.[5]

Houston's design engineers, meanwhile, were hard at work on the spacecraft for the Apollo program. The important choice of mission mode—rendezvous in lunar orbit—had been made in 1962; it dictated two vehicles, whose construction MSC was supervising. North American Aviation, Inc., of Downey, California, was building the command ship, consisting of a command module and a supporting service module—collectively called the command and service module—which carried the crew to lunar orbit and back to earth. A continent away in Bethpage,

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* All three of the Skylab scientist-astronauts were in this first group, selected on 27 June 1965.

Long Island, Grumman Aircraft Engineering Corporation was working on the lunar module, a spidery-looking spacecraft that would set two men down on the moon's surface and return them to the command module, waiting in lunar orbit, for the trip home to earth. Houston engineers had established the basic design of both spacecraft and were working closely with the contractors in building and testing them. All of the important subsystems—guidance and navigation, propulsion and attitude control, life-support and environmental control—were MSC responsibilities; and beginning with *Gemini 4* control of all missions passed to Houston once the booster had cleared the launch pad.[6]

Since the drama of spaceflight was inherent in the risks taken by the men in the spacecraft, public attention was most often directed at the Houston operation. This superficial and news-conscious view, though true enough during flight and recovery, paid scant attention to the launch vehicles and to the complex operations at the launch site, without which the comparatively small spacecraft could never have gone anywhere, let alone to the moon.

The Saturn launch vehicles were the responsibility of NASA's largest field center, the George C. Marshall Space Flight Center, 10 kilometers southwest of Huntsville in northern Alabama. Marshall had been built around the most famous cadre in rocketry—Wernher von Braun and his associates from Peenemünde, Germany's center for rocket research during World War II. Driven since his schoolboy days by the dream of spaceflight, von Braun in 1965 was well on the way to seeing that dream realized, for the NASA center of which he was director was supervising the development of the Saturn V, the monster three-stage rocket that would power the moon mission.[7]

Marshall Space Flight Center was shaped by experiences quite unlike those that molded the Manned Spacecraft Center. The rocket research and development that von Braun and his colleagues began in Germany in the 1930s had been supported by the German army, and their postwar work continued under the supervision of the U.S. army. In 1950 the group moved to Redstone Arsenal outside Huntsville, where it functioned much as an army arsenal does, not only designing launch vehicles but building them as well. From von Braun all the way down, Huntsville's rocket builders were dirty-hands engineers, and they had produced many Redstone and Jupiter missiles. In 1962 von Braun remarked in an article written for a management magazine, "we can still carry an idea for a space vehicle . . . from the concept through the entire development cycle of design, development, fabrication, and testing." That was the way he felt his organization should operate, and so it did; of 10 first stages built for the Saturn I, 8 were turned out at Marshall.[8]

The sheer size of the Apollo task required a division of responsibility, and the MSC and Marshall shares were sometimes characterized as "above and below the instrument unit."* To be sure, the booster and its payload were not completely independent, and the two centers cooperated whenever necessary. But on the whole, as Robert Gilruth said of their roles, "They built a damned good rocket and we built a damned good spacecraft." Von Braun, however, whose thinking had never been restricted to launch vehicles alone, aspired to a larger role for Marshall: manned operations, construction of stations in earth orbit, and all phases of a complete space program—which would eventually encroach on Houston's responsibilities.[9]

But as long as Marshall was occupied with Saturn, that aspiration was far from realization. Saturn development was proceeding well in 1965. The last test flights of the Saturn I were run off that year and preparations were under way for a series of Saturn IB shots.† In August each of the three stages of the Saturn V was successfully static-fired at full thrust and duration. Not only that, but the third stage was fired, shut down, and restarted, successfully simulating its role of injecting the Apollo spacecraft into its lunar trajectory. Flight testing remained to be done, but Saturn V had taken a long stride.[10]

Confident though they were of ultimate success, Marshall's 7300 employees could have felt apprehensive about their future that summer. After Saturn V there was nothing on the drawing boards. Apollo still had a long way to go, but most of the remaining work would take place in Houston. Von Braun could hardly be optimistic when he summarized Marshall's prospects in a mid-August memo. Noting the trend of spaceflight programs, especially booster development, and reminding his coworkers that 200 positions were to be transferred from Huntsville to Houston, von Braun remarked that it was time "to turn our attention to the future role of Marshall in the nation's space program." As a headquarters official would later characterize it, Marshall in 1965 was "a tremendous solution looking for a problem." Sooner than the other centers, Marshall was seriously wondering, "What do we do after Apollo?"[11]

Some 960 kilometers southeast of Huntsville, halfway down the Atlantic coast of Florida, the third of the manned spaceflight centers had no time for worry about the future. The John F. Kennedy Space Center, usually referred to as "the Cape" from its location adjacent to Cape Canaveral, was in rapid expansion. What had started as the Launch Operations Directorate of Marshall Space Flight Center was, by 1965, a busy center with a total work force (including contractor employees) of 20 000 people. In April construction teams topped off the huge Vehicle

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* The instrument unit was the electronic nerve center of inflight rocket control and was located between the booster's uppermost stage and the spacecraft.

† The Saturn IB or "uprated Saturn I" was a two-stage rocket like its predecessor but with an improved and enlarged second stage.

Assembly Building, where the 110-meter Saturn V could be assembled indoors. Two months later road tests began for the mammoth crawler-transporter that would move the rocket, complete and upright, to one of two launch pads. Twelve kilometers eastward on the Cape, NASA launch teams were winding up Saturn I flights and working Gemini missions with the Air Force.[12]

Under the directorship of Kurt Debus, who had come from Germany with von Braun in 1945, KSC's responsibilities included much more than launching rockets. At KSC all of the booster stages and spacecraft first came together, and though they were thoroughly checked and tested by their manufacturers, engineers at the Cape had to make sure they worked when put together. One of KSC's largest tasks was the complete checkout of every system in the completed vehicle, verifying that NASA's elaborate system of "interface control" actually worked. If two vehicle components, manufactured by different contractors in different states, did not function together as intended, it was KSC's job to find out why and see that they were fixed. Checkout responsibility brought KSC into close contact not only with the two other NASA centers but with all of the major contractors.[13]

Responsibility for orchestrating the operations of the field centers and their contractors lay with the Office of Manned Space Flight (OMSF) at NASA Headquarters in Washington. One of three program offices, OMSF reported to NASA's third-ranking official, Associate Administrator Robert C. Seamans, Jr. Ever since the Apollo commitment in 1961, OMSF had overshadowed the other program offices (the Office of Space Science and Applications and the Office of Advanced Research and Technology) not only in its share of public attention but in its share of the agency's budget.

Directing OMSF in 1965 was George E. Mueller (pronounced "Miller"), an electrical engineer with a doctorate in physics and 23 years' experience in academic and industrial research. Before taking the reins as associate administrator for manned spaceflight in 1963, Mueller had been vice president of Space Technology Laboratories, Inc., in Los Angeles, where he was deeply involved in the Air Force's Minuteman missile program. He had spent his first year in Washington reorganizing OMSF and gradually acclimatizing the field centers to his way of doing business. Considering centralized control to be the prime requisite for achieving the Apollo goal, Mueller established an administrative organization that gave Headquarters the principal responsibility for policy-making while delegating as much authority as possible to the centers.[14]

Mueller had to pick his path carefully, for the centers had what might be called a "States'-rights attitude" toward direction from Headquarters and had enjoyed considerable autonomy. Early in his tenure, convinced that Apollo was not going to make it by the end of the decade, Mueller went against center judgment to institute "all-up" testing for the Saturn V. This called for complete vehicles to be test-flown with all stages functioning the first time—a radical departure from the stage-by-stage testing NASA and NACA had previously done, but a procedure that had worked for Minuteman. It would save time and money—if it worked—but would put a substantial burden on reliability and quality control. Getting the centers to accept all-up testing was no small feat; when it succeeded, Mueller's stock went up. Besides putting Apollo back on schedule, this practice increased the possibility that some of the vehicles ordered for Apollo might become surplus and thus available for other uses.[15]

DIRECTIONS FOR MANNED SPACEFLIGHT

In an important sense the decision to shoot for the moon short-circuited conventional schemes of space exploration. From the earliest days of serious speculation on exploration of the universe, the Europeans who had done most of it assumed that the first step would be a permanent station orbiting the earth. Pioneers such as Konstantin Eduardovich Tsiolkowskiy and Hermann Oberth conceived such a station to be useful, not only for its vantage point over the earth below, but as a staging area for expeditions outward. Wernher von Braun, raised in the European school, championed the earth-orbiting space station in the early 1950s in a widely circulated national magazine article.[16]

There were sound technical reasons for setting up an orbiting way-station en route to distant space destinations. Rocket technology was a limiting factor; building a station in orbit by launching its components on many small rockets seemed easier than developing the huge ones required to leave the earth in one jump. Too, a permanent station would provide a place to study many of the unknowns in manned flight, man's adaptability to weightlessness being an important one. There was, as well, a wealth of scientific investigation that could be done in orbit. The space station was, to many, the best way to get into space exploration; all else followed from that.[17]

The sense of urgency pervading the United States in the year following Sputnik was reflected in the common metaphor, "the space race." It was a race Congress wanted very much to win, even if the location of the finish line was uncertain. In late 1958 the House Select Committee on Space began interviewing leading scientists, engineers, corporate executives, and government officials, seeking to establish goals beyond Mercury. The committee's report, *The Next Ten Years in Space,* concluded that a space station was the next logical step. Wernher von Braun and his staff at the Army Ballistic Missile Agency presented a similar view in briefings for NASA. Both a space station and a manned lunar landing were included in a list of goals given to Congress by NASA Deputy Administrator Hugh Dryden in February 1959.[18]

Later that year NASA created a Research Steering Committee on Manned Space Flight to study possibilities for post-Mercury programs. That committee is usually identified as the progenitor of Apollo; but at its first meeting members placed a space station ahead of the lunar landing in a list of logical steps for a long-term space program. Subsequent meetings debated the research value of a station versus a moon landing, advocated as a true "end objective" requiring no justification in terms of some larger goal to which it contributed. Both the space station and the lunar mission had strong advocates, and Administrator T. Keith Glennan declined to commit NASA either way. Early in 1960, however, he did agree that after Mercury the moon should be the end objective of manned spaceflight.[19]

Still, there remained strong justification for the manned orbital station and plenty of doubt that rocket development could make the lunar voyage possible at any early date. Robert Gilruth told a symposium on manned space stations in the spring of 1960 that NASA's flight missions were a compromise between what space officials would like to do and what they could do. Looking at all the factors involved, Gilruth said, "It appears that the multi-man earth satellites are achievable . . . , while such programs as manned lunar landing and return should not be directly pursued at this time." Heinz H. Koelle, chief of the Future Projects Office at Marshall Space Flight Center, offered the opinion that a small laboratory was the next logical step in earth-orbital operations, with a larger (up to 18 metric tons) and more complex one coming along when rocket payloads could be increased.[20] This was the Marshall viewpoint, frequently expressed up until 1962.

During 1960, however, manned flight to the moon gained ascendancy. In the fiscal 1961 budget hearings, very little was said about space stations; the budget proposal, unlike the previous year's, sought no funds for preliminary studies. The agency's long-range plan of January 1961 dropped the goal of a permanent station by 1969; rather, the Space Task Group was considering a much smaller laboratory—one that could fit into the adapter section that supported the proposed Apollo spacecraft on its launch vehicle.[21]

Then, in May 1961, President John F. Kennedy all but sealed the space station's fate with his proclamation of the moon landing as America's goal in space. It was the kind of challenge American technology could most readily accept: concise, definite, and measurable. Success or failure would be self-evident. It meant, however, that all of the efforts of NASA and much of aerospace industry would have to be narrowly focused. Given a commitment for a 20-year program of methodical space development, von Braun's 1952 concept might have been accepted as the best way to go. With only 8½ years it was out of the question. The United States was going to pull off its biggest act first, and there would be little time to think about what might follow.

SPACE STATIONS AFTER 1962

The decision to go for the moon did not in itself rule out a space station; it made a large or complex one improbable, simply because there would be neither time nor money for it. At Marshall, von Braun's group argued during the next year for reaching the moon by earth-orbit rendezvous—the mission mode whereby a moon-bound vehicle would be fueled from "tankers" put into orbit near the earth. Compared to the other two modes being considered—direct flight and lunar-orbit rendezvous*—this seemed both safer and more practical, and Marshall was solidly committed to it. In studies done in 1962 and 1963, Marshall proposed a permanent station capable of checking out and launching lunar vehicles. In June 1962, however, NASA chose lunar-orbit rendezvous for Apollo, closing off prospects for extensive earth-orbital operations as a prerequisite for the lunar landing.[22]

From mid-1962, therefore, space stations were proper subjects for advanced studies—exercises to identify the needs of the space program and pinpoint areas where research and development were required. Much of this future-studies work went to aerospace contractors, since NASA was heavily engaged with Apollo. The door of the space age had just opened, and it was an era when, as one future projects official put it, "the sky was not the limit" to imaginative thinking. Congress was generous, too; between 1962 and 1965 it appropriated $70 million for future studies. A dozen firms received over 140 contracts to study earth-orbital, lunar, and planetary missions and the spacecraft to carry them out. There were good reasons for this intensive planning. As a NASA official told a congressional committee, millions of dollars in development costs could be saved by determining what *not* to try.[23]

Langley Research Center took the lead in space-station studies in the early 1960s. After developing a concept for a modest station in the summer of 1959—one that foreshadowed most of Skylab's purposes and even considered the use of a spent rocket stage—Langley's planners went on to consider much bigger stations. Artificial gravity, to be produced by rotating the station, was one of their principal interests from the start. Having established an optimum rate and radius of rotation (4 revolutions per minute and 25 meters), they studied a number of configurations, settling finally on a hexagonal wheel with spokes radiating from a central control module. Enclosing nearly 1400 cubic meters of work space and accommodating 24 to 36 crewmen, the station would weigh 77 metric tons at launch.[24]

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* In direct flight the vehicle travels from the earth to the moon by the shortest route, brakes, and lands; it returns the same way. This requires taking off with all the stages and fuel needed for the round trip, dictating a very large booster. In lunar-orbit rendezvous two spacecraft are sent to the moon: a landing vehicle and an earth-return vehicle. While the former lands, the latter stays in orbit awaiting the lander's return; when they have rejoined, the lander is discarded and the crew comes home in the return ship. Von Braun and his group adopted earth-orbit rendezvous as doctrine.

Getting something of this size into orbit was another problem. Designers anticipated severe problems if the station were launched piecemeal and assembled in orbit—a scheme von Braun had advocated 10 years earlier—and began to consider inflatable structures. Although tests were run on an 8-meter prototype, the concept was finally rejected, partly on the grounds that such a structure would be too vulnerable to meteoroids. As an alternative Langley suggested a collapsible structure that could be erected, more or less umbrella-fashion, in orbit and awarded North American Aviation a contract to study it.[25]

Langley's first efforts were summarized in a symposium in July 1962. Papers dealt with virtually all of the problems of a large rotating station, including life support, environmental control, and waste management. Langley engineers felt they had made considerable progress toward defining these problems; they were somewhat concerned, however, that their proposals might be too large for NASA's immediate needs.[26]

Similar studies were under way in Houston, where early in 1962 MSC began planning a large rotating station to be launched on the Saturn V. As with Langley's proposed stations, Houston's objectives were to assess the problems of living in space and to conduct scientific and technological research. Resupply modules and relief crews would be sent to the station with the smaller Saturn IB and an Apollo spacecraft modified to carry six men, twice its normal complement. MSC's study proposed to put the station in orbit within four years.[27]

By the fall of 1962 the immediate demands of Apollo had eased somewhat, allowing Headquarters to give more attention to future programs. In late September Headquarters officials urged the centers to go ahead with their technical studies even though no one could foresee when a station might fly. Furthermore, it had begun to look as though rising costs in Apollo would reduce the money available for future programs. Responses from both MSC and Langley recognized the need for simplicity and fiscal restraint; but the centers differed as to the station's mission. Langley emphasized a laboratory for advanced technology. Accordingly, NASA's offices of space science and advanced technology should play important roles in planning. MSC considered the station's major purpose to be a base for manned flights to Mars.[28]

The following month Joseph Shea, deputy director for systems in the Office of Manned Space Flight, sought help in formulating future objectives for manned spaceflight. In a letter to the field centers and Headquarters program offices, Shea listed several options being considered by OMSF, including an orbiting laboratory. Such a station was thought to be feasible, he said, but it required adequate justification to gain approval. He asked for recommendations concerning purposes, configurations, and specific scientific and engineering requirements for the space station, with two points defining the context: the importance of a space station program to science, technology, or national goals; and the unique characteristics of such a station and why such a program could not be accomplished by using Mercury, Gemini, Apollo, or unmanned spacecraft.[29] Public statements and internal correspondence during the next six months stressed the agency's intention to design a space station that would serve national needs.[30]

By mid-1963, NASA had a definite rationale for an earth-orbiting laboratory. The primary mission on early flights would be to determine whether man could live and work effectively in space for long periods. The weightlessness of space was a peculiar condition that could not be simulated on earth—at least not for more than 30 seconds in an airplane. No one could predict either the long-term effects of weightlessness or the results of a sudden return to normal gravity. These biomedical concerns, though interesting in themselves, were part of a larger goal: to use space stations as bases for interplanetary flight. A first-generation laboratory would provide facilities to develop and qualify the various systems, structures, and operational techniques needed for an orbital launch facility or a larger space station. Finally, a manned laboratory had obvious uses in the conduct of scientific research in astronomy, physics, and biology.

SIZING UP A SPACE STATION

Although mission objectives and space-station configuration were related, the experiments did not necessarily dictate a specific design. NASA could test man's reaction to weightlessness in a series of gradually extended flights beginning with Gemini hardware, a low-cost approach particularly attractive to Washington. An alternate plan would measure astronauts' reaction to varying levels of artificial gravity within a large rotating station. Joseph Shea pondered the choices at a conference in August 1963:

> Is a minimal Apollo-type MOL [Manned Orbiting Laboratory] sufficient for the performance of a significant biomedical experiment? Or perhaps the benefits of a truly multi-purpose MOL are so overwhelming . . . that one should not spend unnecessary time and

> effort . . . building small stations, but, rather, proceed immediately with the development of a large laboratory in space.[31]

Whatever choice NASA made, it could select from a wide range of space-station concepts generated since 1958 by the research centers and aerospace contractors. The possibilities fit into three categories: small, medium, and large.

The minimum vehicle, emphasizing the use of developed hardware, offered the shortest development time and lowest cost. Most often mentioned in this category was Apollo, the spacecraft NASA was developing for the lunar landings. There were three basic parts to Apollo: command, service, and lunar modules. The conical command module carried the crew from launch to lunar orbit and back to reentry and recovery, supported by systems and supplies in the cylindrical service module to which it was attached until just before reentry. Designed to support three men, the CM was roomy by Gemini standards, even though its interior was no larger than a small elevator. Stowage space was at a premium, and not much of its instrumentation could be removed for operations in earth orbit. One part of the service module was left empty to accommodate experiments, but it was unpressurized and could only be reached by extravehicular activity. The lunar module was an even more specialized and less spacious craft. It was in two parts: a pressurized ascent stage containing the life-support and control systems, and a descent stage, considerably larger but unpressurized. The descent stage could be fitted with a fair amount of experiments; but like the service module, it was accessible only by extravehicular activity.[32]

The shortage of accessible space was an obvious difficulty in using Apollo hardware for a space station. Proposals had been made to add a pressurized module that would fit into the adapter area, between the launch vehicle and the spacecraft, but this tended to offset the advantages of using existing hardware. Still, in July 1963, with the idea of an Apollo laboratory gaining favor, Headquarters asked Houston to supervise a North American Aviation study of an Extended Apollo mission.[33]

North American, MSC's prime Apollo contractor, had briefly considered the Space Task Group's proposal for an Apollo laboratory two years earlier. Now company officials revived the idea of the module in the adapter area, which had grown considerably during the evolution of the Saturn design. Though the study's primary objective was to identify the modifications required to support a 120-day flight, North American also examined the possibility of a one-year mission sustained by periodic resupply of expendables. Three possible configurations were studied: an Apollo command module with enlarged subsystems; Apollo with an attached module supported by the command module; and Apollo plus a new, self-supporting laboratory module. A crew of two was postulated for the first concept; the others allowed a third astronaut.[34]

Changing the spacecraft's mission would entail extensive modifications but no basic structural changes. Solar cells would replace the standard hydrogen-oxygen fuel cells, which imposed too great a weight penalty. In view of the adverse effects of breathing pure oxygen for extended periods, North American recommended a nitrogen-oxygen atmosphere, and instead of the bulky lithium hydroxide canister to absorb carbon dioxide, the study proposed to use more compact and regenerable molecular sieves.* Drawing from earlier studies, the study group prepared a list of essential medical experiments and established their approximate weights and volumes, as well as the power, time, and workspace required to conduct them. It turned out that the command module was too small to support more than a bare minimum of these experiments, and even with the additional module and a third crewman there would not be enough time to perform all of the desired tests.[35]

North American's study concluded that all three concepts were technically sound and could perform the required mission. The command module alone was the least costly, but reliance on a two-man crew created operational liabilities. Adding a laboratory module, though obviously advantageous, increased costs by 15–30% and posed a weight problem. Adding the dependent module brought the payload very near the Saturn IB's weight-lifting limit, while the independent module exceeded it. Since NASA expected to increase the Saturn's thrust by 1967, this was no reason to reject the concept; however, it represented a problem that would persist until 1969: payloads that exceeded the available thrust. North American recommended that any follow-up study be limited to the Apollo plus a dependent module, since this had the greatest applicability to all three mission proposals. The findings were welcomed at Headquarters, where the funding picture for post-Apollo programs remained unclear. The company was asked to continue its investigation in 1964, concentrating on the technical problems of extending the life of Apollo subsystems.[36]

Several schemes called for a larger manned orbiting laboratory that would support four to six men for a year with ample room for experiments. Like the minimum vehicle, the medium-sized laboratory was usually a zero-gravity station that could be adapted to provide artificial gravity. Langley's Manned Orbiting Research Laboratory, a study begun in late 1962, was probably the best-known example of this type: a four-man canister 4 meters in diameter and 7 meters long containing its own life-support systems. Although the laboratory itself would have to be developed, launch vehicles and ferry craft were proven hardware. A Saturn IB or the Air Force's Titan III could launch the laboratory, and Gemini spacecraft would carry the crews. Another advantage was simplicity: the module would be launched in its final configuration, with no requirement for assembly or deployment in orbit. Use of the Gemini spacecraft meant there would be no new operational problems to solve. Even so, the initial cost was unfavorable and Headquarters considered the complicated program of crew rotation a disadvantage.[37]

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* Molecular sieves contain a highly absorbent mineral, usually a zeolite (a potassium aluminosilicate), whose structure is a 3-dimensional lattice with regularly spaced channels of molecular dimensions; the channels comprise up to half the volume of the material. Molecules (such as carbon dioxide) small enough to enter these channels are absorbed, and can later be driven off by heating, regenerating the zeolite for further use.

Large station concepts, like MSC's Project Olympus, generally required a Saturn V booster and separately launched crew-ferry and logistics spacecraft. Crew size would vary from 12 to 24, and the station would have a five-year life span. Proposed large laboratories ranged from 46 to 61 meters in diameter, and typically contained 1400 cubic meters of space. Most provided for continuous rotation to create artificial gravity, with non-rotating central hubs for docking and zero-gravity work. Such concepts represented a space station in the traditional sense of the term, but entailed quite an increase in cost and development time.[38]

Despite the interest in Apollo as an interim laboratory, Houston was more enthusiastic about a large space station. In June 1963, MSC contracted for two studies, one by Douglas Aircraft Company for a zero-gravity station and one with Lockheed for a rotating station. Study specifications called for a Saturn V booster, a hangar to enclose a 12-man ferry craft, and a 24-man crew. Douglas produced a cylindrical design 31 meters long with pressurized compartments for living quarters and recreation, a command center, a laboratory that included a one-man centrifuge to simulate gravity for short periods, and a hangar large enough to service four Apollos. The concept, submitted in February 1964, was judged to be within projected future capabilities, but the work was discontinued because there was no justification for a station of that size.[39]

Lockheed's concept stood a better chance of eventual adoption, since it provided artificial gravity—favored by MSC engineers, not simply for physiological reasons but for its greater efficiency. As one of them said, "For long periods of time [such as a trip to Mars], it might just be easier and more comfortable for man to live in an environment where he knew where the floor was, and where his pencil was going to be, and that sort of thing." Lockheed's station was a Y-shaped module with a central hub providing a zero-gravity station and a hangar for ferry and logistics spacecraft. Out along the radial arms, 48 men could live in varying levels of artificial gravity.[40]

While studies of medium and large stations continued, NASA began plans in 1964 to fly Extended Apollo as its first space laboratory. George Mueller's all-up testing decision in November 1963 increased the likelihood of surplus hardware by reducing the number of launches required in the moon program. Officials refused to predict how many flights might be eliminated, but 1964 plans assumed 10 or more excess Saturns.

Dollar signs, however, had become more important than surplus hardware. Following two years of generous support, Congress reduced NASA's budget for fiscal 1964 from $5.7 to $5.1 billion. The usually optimistic von Braun told Heinz Koelle in August 1963, "I'm convinced that in view of NASA's overall funding situation, this space station thing will not get into high gear in the next few years. Minimum C-IB approach [Saturn IB and Extended Apollo] is the only thing we can afford at this time." The same uncertainty shaped NASA's planning the following year. In April 1964, Koelle told von Braun that Administrator James Webb had instructed NASA planners to provide management with "various alternative objectives and missions and their associated costs and consequences rather than detailed definition of a single specific long term program." Von Braun's wry response summed up NASA's dilemma: "Yes, that's the new line at Hq., so they can switch the tack as the Congressional winds change."[41]

At the FY 1965 budget hearings in February 1964, testimony concerning advanced manned missions spoke of gradual evolution from Apollo-Saturn hardware to more advanced spacecraft. NASA had not made up its mind about a post-Apollo space station. Two months later, however, Michael Yarymovych, director for earth-orbital-mission studies, spelled out the agency's plans to the First Space Congress meeting at Cocoa Beach, Florida. Extended Apollo, he said, would be an essential element of an expanding earth-orbital program, first as a laboratory and later as a logistics system. Some time in the future, NASA would select a more sophisticated space station from among the medium and large concepts under consideration. Mueller gave credence to his remarks the following month by placing Yarymovych on special assignment to increase Apollo system capabilities.[42] Meanwhile, a project had appeared that was to become Skylab's chief competitor for the next five years: an Air Force orbiting laboratory.

AIR FORCE SEEKS ROLE IN SPACE

For a decade after Sputnik, the U.S. Air Force and NASA vied for roles in space. The initial advantage lay with the civilian agency, for the Space Act of 1958 declared that "activities in space should be devoted to peaceful purposes." In line with this policy, the civilian Mercury project was chosen over the Air Force's "Man in Space Soonest" as America's first manned space program.[43] But the Space Act also gave DoD responsibility for military operations and development of weapon systems; consequently the Air Force sponsored studies over the next three years to define space bombers, manned spy-satellites, interceptors, and a command and control center. In congressional briefings after the 1960 elections, USAF spokesmen stressed the theme that "military space, defined as space out to 10 Earth diameters, is the battleground of the future."[44]

For all its efforts, however, the Air Force could not convince its civilian superiors that space was the next battleground. When Congress added $86 million to the Air Force budget for its manned space glider, Dyna-Soar, Secretary of Defense Robert S. McNamara refused to spend the money. DoD's director of defense research and development testified to a congressional committee, "there is no definable need at this time, or military requirement at this time" for a manned military space program. It was wise to advance American space technology, since military uses might appear; but "NASA can develop much of it or even most of it." Budget requests in 1962 reflected the Air Force's loss of position. NASA's $3.7 billion authorization was three times what the Air Force got for space activities; three years earlier the two had been almost equal.[45]

Throughout the Cold War, Russian advances proved the most effective stimuli for American actions; so again in August 1962 a Soviet space spectacular strengthened the Air Force argument for a space role. Russia placed two spacecraft into similar orbits for the first time. *Vostok 3* and *4* closed to within 6½ kilometers, and some American reports spoke of a rendezvous and docking. Air Force supporters saw military implications in the Soviet feat, prompting McNamara to reexamine Air Force plans. Critics questioned the effectiveness of NASA-USAF communication on technical and managerial problems. In response, James Webb created a new NASA post, deputy associate administrator for defense affairs, and named Adm. Walter F. Boone (USN, ret.) to it in November 1962. In the meantime, congressional demands for a crash program had subsided, partly because successful NASA launches* bolstered confidence in America's civilian programs.[46]

The Cuban missile crisis occupied the Pentagon's attention through much of the fall, but when space roles were again considered, McNamara showed a surprising change of attitude. Early in 1962 Air Force officials had begun talking about a "Blue Gemini" program, a plan to use NASA's Gemini hardware in early training missions for rendezvous and support of a military space station. Some NASA officials welcomed the idea as a way to enlarge the Gemini program and secure DoD funds. But when Webb and Seamans sought to expand the Air Force's participation in December 1962, McNamara proposed that his department assume responsibility for all America's manned spaceflight programs. NASA officials successfully rebuffed this bid for control, but did agree, at McNamara's insistence, that neither agency would start a new manned program in near-earth orbit without the other's approval.[47] The issue remained alive for months. At one point the Air Force attempted to gain control over

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* *Mariner 2* was launched toward Venus on 27 August 1962; in October came two Explorer launches and the Mercury flight of Walter M. Schirra; on 16 November NASA conducted its third successful Saturn I test flight.

NASA's long-range planning. An agreement was finally reached in September protecting NASA's right to conduct advanced space-station studies but also providing for better liaison through the Aeronautics and Astronautics Coordinating Board (the principal means for formal liaison between the two agencies). The preamble to the agreement expressed the view that, as far as practicable, the two agencies should combine their requirements in a common space-station.[48]

McNamara's efforts for a joint space-station were prompted in part by Air Force unhappiness with Gemini. Talk of a "Blue Gemini" faded in 1963 and Dyna-Soar lost much of its appeal. If NASA held to its schedules, Gemini would fly two years before the space glider could make its first solo flight. On 10 December Secretary McNamara terminated the Dyna-Soar project, transferring a part of its funds to a new project, a Manned Orbiting Laboratory (MOL).[49]

With MOL the Air Force hoped to establish a military role for man in space; but since the program met no specific defense needs, it had to be accomplished at minimum cost. Accordingly, the Air Force planned to use proven hardware: the Titan IIIC launch vehicle, originally developed for the Dyna-Soar, and a modified Gemini spacecraft. Only the system's third major component, the laboratory, and its test equipment would be new. The Titan could lift 5700 kilograms in addition to the spacecraft; about two-thirds of this would go to the laboratory, the rest to test equipment. Initial plans provided 30 cubic meters of space in the laboratory, roughly the volume of a medium-sized house trailer. Laboratory and spacecraft were to be launched together; when the payload reached orbit, two crewmen would move from the Gemini into the laboratory for a month's occupancy. Air Force officials projected a cost of $1.5 billion for four flights, the first in 1968.[50]

The MOL decision raised immediate questions about the NASA-DoD pact on cooperative development of an orbital station. Although some outsiders considered the Pentagon's decision a repudiation of the Webb-McNamara agreement, both NASA and DoD described MOL as a single military project rather than a broad space program. They agreed not to construe it as the National Space Station, a separate program then under joint study; and when NASA and DoD established a National Space Station Planning Subpanel in March 1964 (as an adjunct of the Aeronautics and Astronautics Coordinating Board), its task was to recommend a station that would follow MOL. Air Force press releases implied that McNamara's approval gave primary responsibility for space stations to the military, while NASA officials insisted that the military program complemented its own post-Apollo plans. Nevertheless, concern that the two programs might appear too similar prompted engineers at Langley and MSC to rework their designs to look less like MOL.[51]

Actually, McNamara's announcement did not constitute program approval, and for the next 20 months MOL struggled for recognition and adequate funding. Planning went ahead in 1964 and some contracts were let, but the deliberate approach to MOL reflected political realities. In September Congressman Olin Teague (Dem., Tex.), chairman of the House Subcommittee on Manned Space Flight and of the Subcommittee on NASA Oversight, recommended that DoD adapt Apollo to its needs. Shortly after the 1964 election, Senate space committee chairman Clinton Anderson (Dem., N.M.) told the president that he opposed MOL; he believed the government could save more than a billion dollars in the next five years by canceling the Air Force project and applying its funds to an Extended Apollo station. Despite rumors of MOL's impending cancellation, the FY 1966 budget proposal included a tentative commitment of $150 million.[52]

The Bureau of the Budget, reluctant to approve two programs that seemed likely to overlap, allocated funds to MOL in December with the understanding that McNamara would hold the money pending further studies and another review in May. DoD would continue to define military experiments, while NASA identified Apollo configurations that might satisfy military requirements. A joint study would consider MOL's utility for non-military missions. A NASA-DoD news release on 25 January 1965 said that overlapping programs must be avoided. For the next few years both agencies would use hardware and facilities "already available or now under active development" for their manned spaceflight programs—at least "to the maximum degree possible."[53]

In February a NASA committee undertook a three-month study to determine Apollo's potential as an earth-orbiting laboratory and define key scientific experiments for a post-Apollo earth-orbital flight program. Although the group had worked closely with an Air Force team, the committee's recommendations apparently had little effect on MOL, the basic concept for which was unaltered by the review. More important, the study helped NASA clarify its own post-Apollo plans.[54]

Since late 1964, advocates of a military space program had increased their support for MOL, the House Military Operations Subcommittee recommending in June that DoD begin full-scale development without further delay. Two weeks later a member of the House Committee on Science and Astronautics urged a crash program to launch the first MOL within 18 months. Russian and American advances with the Voskhod and Gemini flights—multi-manned missions and space walks—made a military role more plausible. On 25 August 1965, MOL finally received President Johnson's blessing.[55] Asked if the Air Force had clearly established a role for man in space, a Pentagon spokesman indicated that the chances seemed good enough to warrant evaluating man's ability "much more thoroughly than we're able to do on the ground." NASA could not provide the answers because the Gemini spacecraft was too cramped. One newsman wanted to know why the Air Force had abandoned Apollo; the reply was that Apollo's lunar capabilities were in many ways much more than MOL needed. If hindsight suggests that parochial interests were a factor, the Air Force nevertheless had good reasons to shun Apollo. The lunar landing remained America's chief commitment in space. Until that goal was accomplished, an Air Force program using Apollo hardware would surely take second place.[56]

President Calls for NASA's Plans

In early 1964 NASA undertook yet another detailed examination of its plans, this time at the request of the White House. Lyndon Johnson had played an important role in the U.S. space program since his days as the Senate majority leader. Noting that post-Apollo programs were likely to prove costly and complex, the president requested a statement of future space objectives and the research and development programs that supported them.[57]

Webb handed the assignment to an ad hoc Future Programs Task Group. After five months of work, the group made no startling proposals. Their report recognized that Gemini and Apollo were making heavy demands on financial and human resources and urged NASA to concentrate on those programs while deferring "large new mission commitments for further study and analysis." By capitalizing on the "size, versatility, and efficiency" of the Saturn and Apollo, the U.S. should be able to maintain space preeminence well into the 1970s. Early definition of an intermediate set of missions using proven hardware was recommended. Then, a relatively small commitment of funds within the next year would enable NASA to fly worthwhile Extended Apollo missions by 1968. Finally, long-range planning should be continued for space stations and manned flights to Mars in the 1970s.[58]

The report apparently satisfied Webb, who used it extensively in subsequent congressional hearings. It should also have pleased Robert Seamans, since he was anxious to extend the Apollo capability beyond the lunar landing. Others in and outside of NASA found fault with the document. The Senate space committee described the report as "somewhat obsolete," containing "less information than expected in terms of future planning." Committee members faulted its omission of essential details and recommended a 50% cut in Extended Apollo funding, arguing that enough studies had already been conducted. Elsewhere on Capitol Hill, NASA supporters called for specific recommendations. Within the space agency, some officials had hoped for a more ambitious declaration, perhaps a recommendation for a Mars landing as the next manned project. At Huntsville, a future projects official concluded that the plan offered no real challenge to NASA (and particularly to Marshall) once Apollo was accomplished.[59]

In thinking of future missions, NASA officials were aware of how little experience had been gained in manned flight. The longest Mercury mission had lasted less than 35 hours. Webb and Seamans insisted before congressional committees that the results of the longer Gemini flights might affect future planning, and a decision on any major new program should, in any event, be delayed until after the lunar landing. The matter of funding weighed even more heavily against starting a new program. NASA budgets had reached a plateau at $5.2 billion in fiscal 1964, an amount just sufficient for Gemini and Apollo. Barring an increase in available money, new manned programs would have to wait for the downturn in Apollo spending after 1966. There was little support in the Johnson administration or Congress to increase NASA's budget; indeed, Great Society programs and the Vietnam war were pushing in the opposite direction. The Air Force's space program was another problem, since some members of Congress and the Budget Bureau favored MOL as the country's first space laboratory.[60]

MUELLER OPENS APOLLO APPLICATIONS PROGRAM OFFICE

Equally compelling reasons favored an early start of Extended Apollo. A follow-on program, even one using Saturn and Apollo hardware, would require three to four years' lead time. Unless a new program started in 1965 or early 1966, the hiatus between the lunar landing program and its successor would adversely affect the 400 000-member Apollo team. Already, skilled design engineers were nearing the end of their tasks. The problem was particularly worrisome to Marshall, for Saturn IB-Apollo flights would end early in 1968. In the fall of 1964, a Future Projects Group appointed by von Braun began biweekly meetings to consider Marshall's future. In Washington, George Mueller pondered ways of keeping the Apollo team intact. By 1968 or 1969, when the U.S. landed on the moon, the nation's aerospace establishment would be able to produce and fly 8 Apollos and 12 Saturns per year; but Mueller faced a cruel paradox: the buildup of the Apollo industrial base left him no money to employ it effectively after the lunar landing.[61]

Until mid-1965 Extended Apollo was classified as advanced study planning; that summer Mueller moved it into the second phase of project development, project definition. A Saturn-Apollo Applications Program Office was established alongside the Gemini and Apollo offices at NASA Headquarters. Maj. Gen. David Jones, an Air Force officer on temporary duty with NASA, headed the new office; John H. Disher became deputy director, a post he would fill for the next eight years.[62] Little fanfare attended the opening on 6 August 1965. Apollo and Gemini held the spotlight, but establishment of the program office was a significant milestone nonetheless. Behind lay six years of space-station studies and three years of post-Apollo planning. Ahead loomed several large problems: winning fiscal support from the Johnson administration and Congress, defining new relationships between NASA centers, and coordinating Apollo Applications with Apollo. Mueller had advanced the new program's cause in spite of these uncertainties, confident in the worth of Extended Apollo studies and motivated by the needs of his Apollo team. In the trying years ahead, the Apollo Applications Program (AAP) would need all the confidence and motivation it could muster.

2

From Spent Stage to Orbital Cluster, 1965–1966

Within a month after establishing the Apollo Applications Office, Mueller took its preliminary plans to congressional committees. He found no enthusiasm for the program, even though committee members agreed that manned spaceflight should continue after the lunar landing. The straightforward extension of Apollo's capability smacked too much of busywork—of "boring holes in the sky" with frequent long-duration flights, marking time rather than advancing American preeminence in space. Mueller had no better luck convincing NASA's top officials of the intrinsic merit of AAP. James Webb was particularly cautious about starting a costly new program before he was absolutely certain that Apollo was going to achieve its goal. Mueller's concern was twofold: he wanted some options, and he needed a worthwhile program to keep the manned spaceflight organization together. Well aware that Saturn and Apollo could encounter unexpected delays, he wanted a parallel program to maintain the momentum of manned spaceflight. Conversely, if all went well, he wanted to exploit the tremendous capability Apollo was so expensively building up. This was an immediate problem in the case of Marshall Space Flight Center, since after Saturn no major new launch vehicles were planned.[1]

Von Braun saw as clearly as anyone that Marshall must have a broader base than just launch vehicles, and in the period 1962–1965 Huntsville's Future Projects Office studied a number of ideas. When Mueller conceived Apollo Applications as a way to use developed hardware for new purposes, one of these ideas was already under consideration. Called the "spent-stage laboratory," this idea was based on converting, in orbit, an empty rocket stage into living and working space. A conceptual design study started at Marshall scarcely two weeks before Mueller formally established the AAP office at Headquarters. Although Headquarters' studies provided the material for Mueller's presentations to Congress in 1965 and 1966, the Marshall concept quickly got the inside track. Within the next year it became the core on which AAP was built—the vehicle for carrying out the AAP plans of 1964–1965.

Early Proposals to Use Spent Stages

Every orbiting spacecraft is accompanied by the last stage of the rocket that launched it. The empty upper stage is usually in a short-lived orbit, but a small adjustment to its fuel-burning program can stabilize that orbit. As far back as the Peenemünde days, von Braun and his colleagues had speculated on converting an empty stage into a shelter for a small crew. In 1959 the idea was put forth in the report of a study called Project Horizon, carried out by the Army Ballistic Missile Agency. Horizon was the Army's last bid for a role in manned spaceflight: a proposal to establish and maintain an armed outpost on the moon. Heinz Koelle and Frank Williams were Horizon's principal architects, and the report reflected their agency's strong attachment to earth-orbit rendezvous as the principal mode for space operations.[2]

The Horizon study assumed that by 1965 the U.S. would have a permanent station in earth orbit and that it could serve as the base for launching the lunar missions. If no permanent station existed, however, minimum facilities would have to be provided in earth orbit for the crew that refueled the moon-bound rockets. The basic structure for this minimum orbital shelter was to be the empty third stage of the rocket that launched the crew's spacecraft. In orbit, the crew would dock with the empty stage, empty the residual hydrogen from the fuel tank, and fit it out for occupancy with equipment brought along in their spacecraft. As more payloads were orbited in preparation for the lunar mission, more empty stages would be bundled around the first, providing storage space and protecting the crew's quarters from meteoroids and cosmic radiation. Later, spent stages might be assembled into a larger station of the familiar wheel shape. The Horizon report included sketches of a station built from 22 empty stages.[3]

The report was as far as the Army's lunar outpost ever got. Von Braun's group was transferred to NASA; Koelle became director of the Future Projects Office at Marshall Space Flight Center, with Williams as his deputy. For the time being the spent-stage orbital shelter was forgotten in the press of more urgent business.

The next proposal to use a spent stage came from the Douglas Aircraft Company, builder of the Saturn S-IV stage. Douglas had been in the rocket business since the end of the Second World War; its biggest job before Saturn, and its biggest success, was the crash program undertaken in 1957 to build the Thor missile system.* When the Saturn stages were put up for bids in 1960, Douglas won the contract for the S-IV stage. S-IV was the first big stage to use cryogenic propellants (liquid hydrogen and liquid oxygen), and Douglas broke a good deal of technological ground in building it.*

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* Thor was the first intermediate-range missile deployed by a Western power; the first squadron reached England in 1959. Superseded by the intercontinental Atlas and Titan, Thor went on to a long career launching satellites and space probes. Delta, a Thor with an added upper stage, launched satellites through the 1970s.

The S-IV contract was managed by Marshall, and development of the stage brought Douglas and Marshall into a close working relationship. When design or production problems were being worked out, engineers from both organizations pitched in side by side; if Saturn was in trouble, Douglas's problems were Marshall's problems too. Engineers and managers built close professional and personal relationships over the years. It was no different at Houston; MSC's Mercury and Gemini people built similar relationships with their opposite numbers at McDonnell Aircraft Corporation, prime contractor for both the Mercury and Gemini spacecraft.

For all its success with launch vehicles, Douglas had not been able to break into the manned spacecraft business. It was not for lack of trying: the company had bid on Mercury, on the Apollo command module (in a consortium of four companies), and on the lunar module, but without success. In the early 1960s Douglas management determined to change this. They set up a future-studies program to seek "targets of opportunity" in manned spaceflight programs and soon identified small space stations and orbiting laboratories as promising areas for the company to enter. By the end of 1963 Douglas had won several study contracts from NASA and was competing for the Air Force's Manned Orbiting Laboratory.[4]

Douglas got into Apollo Applications, however, by a different route. When the S-IV was superseded by the S-IVB, Douglas won the contract for the new stage, but the S-IV became obsolete. In 1962, the chief engineer for Douglas's Saturn program was put in charge of a study group to see what might be done with the S-IV. The group suggested making it into a small orbiting laboratory.

Exactly how the spent-stage idea jumped the gap between Marshall and Douglas—if it did—is not clear. There were plenty of opportunities. Von Braun traced the origin of Skylab to this first S-IV study, believing it resulted from prodding by Marshall engineers who "were thinking along similar lines at the time." Heinz Koelle remembered discussing a spent-stage idea with von Braun in 1960 and thought von Braun discussed the idea with Douglas engineers, probably in 1961.[5]

The Douglas group compared existing NASA programs with the most likely long-term goals of space exploration and perceived a gap.

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* Centaur was the first, but it was much smaller. Developed by Convair as an upper stage for the Atlas, Centaur helped to launch a number of payloads. See Roger E. Bilstein, *Stages to Saturn: A Technological History of the Apollo/Saturn Launch Vehicles*, NASA SP-4206 (Washington, 1980), and John L. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*, NASA SP-4404 (Washington, 1978).

Gemini and Apollo were narrowly focused programs; neither seemed likely to produce much fundamental information about orbital operations, especially about man's ability to function for long periods in zero gravity. Further, there were no specific plans to qualify hardware components in a true space environment. Sooner or later, both men and systems would have to be qualified, and the study group argued that an orbiting laboratory was the best way to carry out this essential research. Excluding experiment hardware, data handling, and administrative overhead, an S-IV could be outfitted as a laboratory for two men and put in orbit by 1965 at a cost of $220 million.[6]

The S-IV would need very little modification to make it habitable. A meteoroid shield would be fitted around the hydrogen tank before launch. A storage module on top of the stage would carry equipment that could not survive immersion in liquid hydrogen. Arriving in orbit, two crewmen would dock their Gemini spacecraft to the storage module, empty the fuel tank, pressurize it with a nitrogen-oxygen atmosphere, and move equipment from the storage module into the empty stage. In the next hundred days they would conduct more than 70 experiments in physiology, space technology, and orbital operations. The S-IV laboratory carried medical monitoring equipment, including a one-man centrifuge to provide artificial gravity and assess the effect of weightlessness on the human circulatory system. If serious deterioration was observed during the mission, the centrifuge could also be used to recondition the men before their return.[7]

Douglas submitted the studies to the Future Projects Office at Marshall as unsolicited proposals, after which the main ideas were published in professional journals. For several years Douglas continued to propose novel applications for the company's favorite piece of rocket hardware.[8]

The S-IV study group was not aware of it, but the basic idea of a space laboratory had been anticipated within their own company three years earlier. While the first squadron of Thors was being deployed in England, the London *Daily Mail* decided to capitalize on public interest in space for its annual Ideal Home Exhibition. The "Home Show" is one of London's major springtime exhibitions, and the *Mail* chose "A Home in Space" as its theme for 1960. The paper asked American aerospace contractors to submit concepts, and Douglas's proposal was chosen. The company's Advanced Design Section at Santa Monica produced blueprints for a full-scale model and numerous posters. The project intrigued many engineers in the section, and they probably bootlegged at least twice as much engineering time into it as the budget allowed.[9]

The Douglas entry was a space laboratory built into the empty upper stage of a hypothetical launch vehicle. The laboratory was equipped for a crew of four to stay 30 days in earth orbit, making astronomical observations above the atmosphere. The mockup was built inside London's Olympia Exhibition Hall in March 1960, where promoters estimated that over a million people saw it and probably 150 000 walked through it. Back at home it attracted little attention, and the report was filed away and forgotten until Skylab was launched.[10]

MARSHALL SPONSORS THE SPENT STAGE

Douglas's proposals drew no immediate response from Huntsville. Marshall was less involved in space-station studies than either MSC or Langley, and besides, the kind of station NASA might eventually build was not at all clear in 1963. Both Koelle and von Braun sensed that a large station was becoming less likely as the next step in space. Money was going to be a problem, and only a small station was likely to be within NASA's means. MSC's study contract with North American on extending Apollo's time in orbit reflected the trend in thinking, as did Langley's Manned Orbital Research Laboratory studies, kicked off in June 1963 with the award of study contracts to Douglas and Boeing.[11]

An important new factor was George Mueller's desire to have a program running parallel to Apollo—something that could maintain the momentum of the manned spaceflight program in case Apollo got snagged on unforeseen problems or succeeded ahead of schedule.[12] Too, public opinion about Apollo was changing. When Mueller came into NASA, criticism of space spending was reaching a peak. Scientists, among others, were increasingly unhappy; the moon project was absorbing vast sums that would be more productive, in their view, in the unmanned satellite program. Using Apollo hardware to conduct scientific investigations in space would be politically attractive.

Mueller's thinking dovetailed neatly with the situation developing at Marshall in 1964, where the Saturn program was moving smoothly and no new vehicles were in sight. Marshall management was particularly concerned about the Saturn IB—an excellent vehicle for earth-orbital operations, but one with a limited future. Concern was intensified when the Air Force chose the Titan III to launch its Manned Orbiting Laboratory. Koelle spent considerable time in 1964 trying to identify uses for the Saturn IB that would justify keeping it in production. Mueller's interest in developing alternative uses for existing hardware prompted Koelle to resurrect the spent-stage plan and give it a closer look. Seeking a second opinion, Marshall awarded a nine-month, $100 000 contract to North American Aviation to study the utility of spent stages in NASA's contemplated space programs, especially orbital operations and orbiting laboratories.[13]

North American's study considered several schemes, including refueling S-IVB stages in orbit and launching them to the moon or one of the planets, fitting out an S-II stage (the second stage of Saturn V) as an orbital hangar for Apollo spacecraft, and assembling empty S-IVBs into a large station. After the midterm review of the study in January 1964, Marshall added a concept called "Apollo Support Module," which called for using an empty S-IVB fuel tank as working space. The final report in April 1965 recommended this concept for further study. "The large volume of work space," the report said, "can be practically utilized in near-term missions for accomplishing a large quantity of experimentation required for orbital operations support."[14]

Koelle's office had already considered one or two schemes for adapting Saturn hardware, such as using the oxygen tank of the S-IC (Saturn V's first stage) as the structural shell for a laboratory, and something that Koelle referred to as "a minimum space laboratory [growing out of] the Apollo program."[15] Now, with the North American report in hand, the Future Projects Office took it and some of Marshall's own ideas and began to assemble a spent-stage proposal to take to Headquarters.

Initially the idea was a simple undertaking in which an Apollo spacecraft would dock with a spent S-IVB. The crew would go inside to experiment with extravehicular mobility techniques in a protected environment. This could be done without major change to the S-IVB and without pressurizing it; two suited astronauts with cameras and portable lights could gather the necessary data. There was interest in doing more, however: pressurizing the tank and using its 281-cubic-meter volume for living quarters. Ideally a continuing program could be started, with later flights building on and adding to the results of earlier ones. Marshall saw considerable potential in spent stages and regarded them as logical candidates for Extended Apollo—candidates for which Marshall should logically have the responsibility.

It fell to Frank Williams to see this proposal through. At the end of June 1965 Koelle ended his 10-year association with the American space program and took a professorship in the Technical University of Berlin. Williams, who since late 1963 had been von Braun's special assistant for advanced programs, returned to his old shop as its director. At the same time the Future Projects Office was rechristened the Advanced Systems Office.[16] Williams's first job was to finish pulling together the material on the spent-stage proposal for presentation to Headquarters.

Von Braun and Williams took the plans to the Manned Space Flight Management Council on 20 July, proposing to begin a conceptual design study to work out details. Mueller supported the idea and found $150 000 for a four-month study. Williams presented the plans to Marshall's Future Planning Policy Board on 10 August, and on the 20th called the first meeting of the conceptual design study group.[17]

CONCEPT TO DESIGN: BOUNDING THE PROBLEM

The first order of business at the organizational meeting on 25 August was to familiarize the group with the project and to review the plan that had been presented to Management Council. Three configurations of an orbital workshop were to be studied. (*Orbital workshop* was the official designation for the spent stage. As the program progressed it came to include a ground-equipped, Saturn-V-launched, S-IVB workshop; the original concept was then informally referred to as the *wet* workshop to distinguish it from the ground-equipped version, which would never contain fuel—the *dry* workshop. Only the latter would be built.) The "minimum configuration" was simply the empty tank, fitted with a docking port but having no power or life-support systems. An "intermediate configuration" would have an airlock, power, and oxygen (but no carbon dioxide removal), and the crew could work without pressure suits. Finally, the "baseline* configuration" would have a complete environmental control system, as many experiments as weight and space limitations allowed, a power system sized to support the experiments, and positive attitude control. The first two versions could be used in missions 3 to 14 days long and would have only a few experiments; the third could support flights of 14–28 days with a substantial experiment program.[18]

The study picked up momentum slowly. Many questions required answers, which called for a great deal of information. How would power be supplied? What experiments could be ready for the first flight? What would they weigh, and how much power and attitude-control fuel would they require? How was excess propellant to be removed from the tank, and how could the tank openings be sealed? What was the risk from micrometeoroids and how could it be minimized?

Some solutions would be dictated by the limitations of the launch vehicle—orbital altitude and inclination, for example. Some would be settled by fiat ("ground rules"). Others would have to be worked out by a complex series of tradeoffs involving Marshall's Saturn Program Office, Houston's Apollo Program Office, and Douglas. All of this, of course, was simply the kind of systems management that Marshall had been doing for years, and it was just a matter of getting on with it.

Douglas had not been idle in the small space-station field. During 1963 the company had won a contract from Langley for the Manned Orbital Research Laboratory study and one from MSC for a study of a 24-man "Saturn V Class" laboratory. The company had designed, built, and tested a flight-weight airlock under contract to Langley, delivering it in May of 1965. In August of that year Douglas became the prime contractor for the Air Force Manned Orbiting Laboratory. Besides this contract work, the company's Saturn Payload Applications Group had kept an eye on Extended Apollo, maintaining a file of published information on it. That group had assembled a document detailing the use of an empty S-IVB for mobility and maneuvering experiments, with proposals that closely resembled the three workshop configurations being studied at Marshall. The most advanced Douglas version was a pressurized stage remarkably similar to Marshall's most sophisticated workshop. Von Braun, visiting Douglas in September 1965, gave company management an unofficial briefing on the orbital workshop concept (the same presentation Frank Williams had made to Management Council in July) and for the first time Douglas and Marshall learned how closely their ideas paralleled each other.[19]

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* *Baseline* means a point of departure—for hardware, mission, or program—to which subsequent changes are related.

The Manned Spacecraft Center was brought into the picture on 20 October, when Williams and a delegation from Huntsville flew to Houston to brief MSC on the study and what it had accomplished so far. Williams returned to Marshall feeling that his center had stolen a march on MSC with its studies on extravehicular activity; the Houston people, he told von Braun, "seemed surprised at the data and the vigor with which we were working on that area." Much less gratifying was MSC's insistence that extended operations in zero gravity were undesirable. MSC wanted a minimum of 0.1 g to be provided by rotating the workshop on a radius of 20 to 30 meters.[20] This issue would long nag the workshop study, disappearing into limbo some time in 1966 under the pressure of schedule, funding, and design problems.

As the labs came to grips with the various aspects of the workshop mission, Williams and von Braun grew more confident that they had the makings of a substantial program. At the November Management Council meeting, Mueller encouraged von Braun to press on with the study, and at the end of the month Marshall got a chance to sell the program when Mueller and Deputy Administrator Robert Seamans visited Huntsville. Among other briefings they heard a summary of the workshop concept and the results of the conceptual design study, which at that time was concentrating on a minimum-configuration workshop for flight on Saturn-Apollo mission 211, scheduled for August 1968. More than mildly interested, Mueller asked for a presentation at the Management Council meeting three weeks away, showing what Marshall could do on SA-209 and how soon a pressurized workshop could be made ready. He wanted a pressurized version to fly on 209, six months ahead of 211, if possible. Von Braun, sensing a real opportunity for his center, promised the presentation would be ready. He suggested moving the spent-stage study into the project definition phase, and Mueller concurred.[21]

This unexpected surge of interest and the short time available produced immediate action. Williams announced the following day that the workshop must be ready for SA-209. Unfortunately there would be almost no money available from Headquarters; this would mean, among other things, that an airlock would have to be built in-house and financed out of current budgets. Williams wanted a half-day presentation, an honest appraisal of what Marshall could do, ready for von Braun in two weeks.[22]

The next day Williams's office promulgated a new set of guidelines for the study. The primary goal was to "design, fabricate, and test to flight qualifications a pressurized version of the S-IVB workshop for Saturn IB flights 209 or 211." A secondary effort to develop an unpressurized version was to be undertaken simultaneously. An airlock, an environmental control system, and a set of experiments were to be designed and developed, together with ground-support equipment, mockups, training hardware—everything needed to support the mission. Marshall would be wholly responsible for the pressurized version, Douglas for the unpressurized. Flight 209 was the target unless costs, production schedules, or a technological hitch dictated otherwise. Emphasis was on maximum use of flight-qualified hardware, minimum modification of the S-IVB, and minimum cost. The environmental control system should function for 14 days, but a lifetime of 2–6 days was acceptable if necessary to meet the schedule. A pure oxygen atmosphere would be used rather than a mixture of oxygen and nitrogen, because the hardware was simpler. Connections between the Apollo spacecraft and the spent stage would be kept to an absolute minimum. The S-IVB would maintain its attitude until the spacecraft docked, after which the Apollo systems would take over. The priority of experiment categories was laid down: first, basic maneuvering experiments and biomedical observations; second, maintenance, repair, and inspection of spacecraft systems, rescue, and cargo transfer; third, prepackaged experiments where the astronaut functioned primarily as a monitor.[23]

In a follow-up memo, Williams stressed the importance of preparing a proposal that Marshall could execute with confidence. The center was staking its reputation on the workshop. Not only was it important to propose a worthwhile program; it must also be one that the center could accomplish.[24]

CONCEPT TO DESIGN: DEFINING THE WORKSHOP

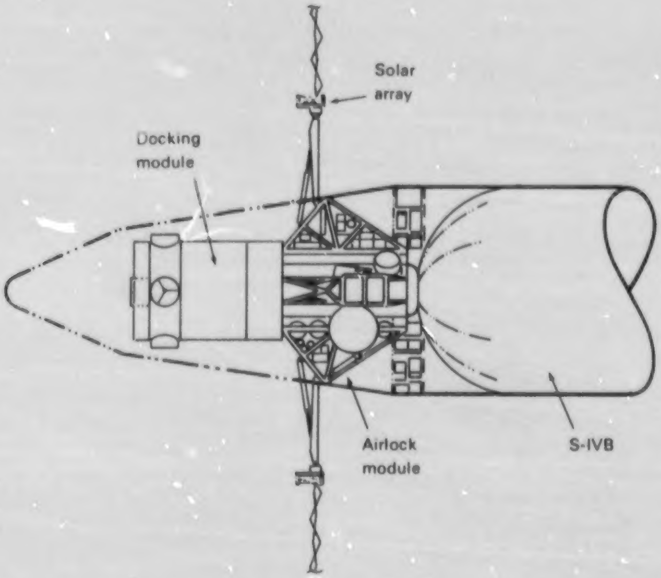
The labs responded with gratifying speed, and after the review by von Braun, Williams took the proposal to Management Council on 21 December. As it had developed, the plan required an additional piece of hardware, a "Spent Stage Experiment Support Module," an airlock that would also carry certain equipment and expendables. For this module, Marshall intended to make use of Douglas's experience in building the Langley airlock, but apparently this was not stressed. After the presentation Mueller suggested that Marshall confer with McDonnell

Aircraft Corporation to see if any Gemini components could be used in the airlock. Gemini production was about to end; Mueller thought that time and money might be saved if any useful hardware could be adapted.[25]

Williams wrote immediately to Charles W. Mathews, Gemini program manager at MSC, asking his help in coordinating talks with McDonnell. Williams wanted a technical briefing at Huntsville as soon as possible, so that Marshall and McDonnell could get acquainted and compare notes. The meeting was held at Houston instead, on 4–5 January 1966, and produced a set of ground rules for the proposals Marshall and McDonnell were to make to Headquarters. The most important rules were to use Gemini-qualified environmental control and electrical power systems and to keep the airlock functionally independent of the S-IVB instrument unit and the Apollo command module. Williams's understanding was that McDonnell would furnish qualified systems to Marshall, which would do the actual fabrication; this would make the best use of Huntsville's civil service personnel and would be in line with Mueller's zero-cost dictum.[26]

The introduction of McDonnell complicated the picture unexpectedly. Marshall was comfortable with Douglas, which had experience designing an airlock. But that airlock, though it was flight weight and had

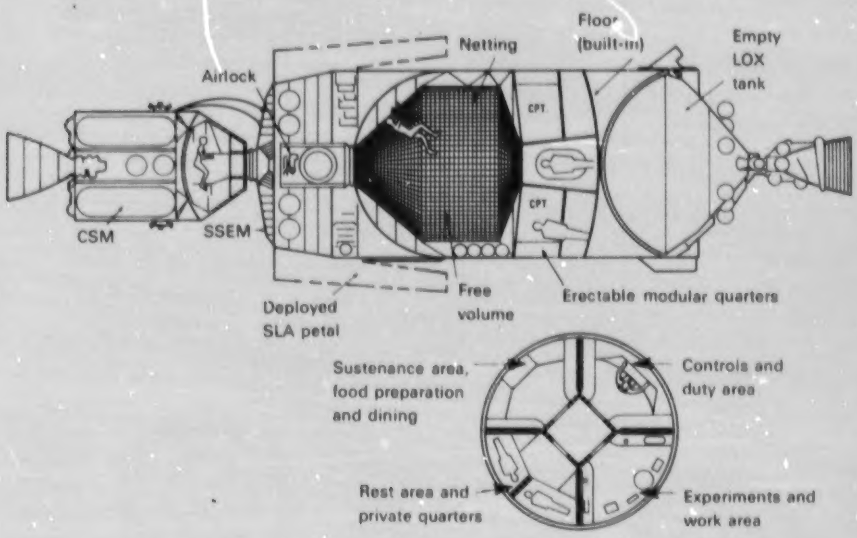
An advanced airlock concept by P. M. Chapman, Douglas Aircraft Co., 20 August 1966.



been extensively tested on the ground, was not fully flight qualified. MSC engineers concluded that upgrading it to flight standards would increase its cost considerably.[27] McDonnell had the advantage of being able to use components already qualified in the Gemini program, at a significant cost saving. But McDonnell and Marshall were strangers, while MSC had worked with the St. Louis firm since the beginning of Mercury. With McDonnell involved in the airlock project, there was a strong argument for MSC to manage it. And since the module would carry two important crew systems (environmental control and life support), Houston could make a case for taking complete responsibility for managing the airlock. MSC's depth of experience in crew systems was unrivaled.

Logically enough, MSC did make this case, and Headquarters listened. MSC, in fact, seemed to be assuming that it would get the project as a matter of right. More than once Frank Williams had the feeling that MSC was not anxious to help him work with McDonnell. By early February the matter required resolution, and on the 11th, during a day-long series of meetings at Houston, von Braun sought it. In Gilruth's office, von Braun argued at length that NASA's interests would be best served if the project went to Huntsville. Unfortunately for his case he went further than that, sketching out plans he had for Marshall's fu-

Early sketch of an orbital workshop prepared at Manned Spacecraft Center.


Airlock
Netting
Floor (built-in)
Empty LOX tank
CPT
CPT
CSM
SSEM
Free volume
Erectable modular quarters
Deployed SLA petal
Sustenance area, food preparation and dining
Controls and duty area
Rest area and private quarters
Experiments and work area

ture—plans that included training men to assemble large structures in orbit. Sharing the responsibility for training was something that MSC could never accept, and in the end von Braun, sensing that he had pressed matters too far, conceded the airlock project to MSC rather than provoke a disruptive confrontation.[28]

This disagreement over management of the airlock indicated that the spent-stage project posed a new problem for manned spaceflight: that of roles and missions for the two field centers. The conversion of an empty rocket stage into a manned workshop blurred the distinction between launch vehicles and spacecraft. No longer did each center have a clearly demarcated territory to work in. A new relationship of the centers to each other and to Headquarters was in the making, and it was not going to be easy to work it out.

After Marshall took itself out of contention for management of the airlock, Douglas still wanted a chance to build it. On 9 March a Douglas delegation went to Washington to brief Mueller on their proposal for an airlock. Mueller was interested in what they had to say, even though, as he told them, the spent-stage project was not yet an approved program and he still "had some selling to do" at higher levels in NASA. He said he had not known about the airlock Douglas had built for Langley, and he was impressed by what they showed him—especially by their proposal to build two units for $4 million. He suggested that Douglas submit proposals.[29]

On 11 March Houston's planners submitted a procurement plan for the airlock, proposing sole-source procurement from McDonnell. Headquarters, however, could not justify sole-source procurement after Douglas's presentation to Mueller; so at the 22 March meeting of Management Council both centers were directed to conduct studies to define the airlock and establish cost and schedule projections for its construction.[30]

Marshall, with so much at stake, began to fear that the airlock's cost might send the whole project down the drain. As a fall-back position to save the workshop project, should that become necessary, the center defined a bare-bones airlock that was just adequate to support their intermediate-configuration workshop. MSC granted three 60-day, $50 000 study contracts to Douglas, McDonnell, and Grumman (prime contractor for the lunar module). Each company was to define an airlock based on its own hardware or concepts: Douglas on the Langley airlock, McDonnell on Gemini systems, and Grumman on modifying the lunar module to serve as an airlock. A source evaluation board chaired by Kenneth S. Kleinknecht, deputy program manager for Gemini at MSC, began considering proposals from the three contractors in late June.[31] On 19 August, Headquarters announced that McDonnell had been selected for negotiation of an airlock contract. With some features added during negotiation, the final agreed price was $10 509 000. Marshall's precautionary study proved unnecessary and was immediately terminated.[32]

While the airlock issue was being thrashed out, the Technical Working Group was busy with modifications to the S-IVB. Before astronauts could enter the hydrogen tank it had to be "passivated"—hydrogen and oxygen tanks vented, high-pressure helium bottles emptied, and the stage's pyrotechnics* deactivated. Hazards inside the tank had to be eliminated. The internal insulation had to be painted a uniform color for a good photographic background. Provision had to be made for equipment to be mounted on the walls; restraints and mobility aids had to be added. By 15 December 1965 a list of stage modifications was drawn up and Marshall asked Douglas for a quick-response estimate of their cost. The reply was $1.5 million to modify stage 209. This was more than Marshall could afford, and negotiations ensued. A second estimate for a slightly different set of changes was $4.5 million for changes to five S-IVBs. Satisfied that this was the best price they were going to get—at least in time for SA-209—Marshall sent the figure to George Mueller on 20 January 1966. He found the quotation disappointingly high and put off all decisions for a month because he still had no budget for Apollo Applications. He told Marshall to determine if the changes could be made in-house and asked for a list of no-cost experiments to be assembled by mid-February.[33]

Just after the new year, Frank Williams had said the spent-stage project was "in high gear," but at the end of January it was stalled by the unsettled funding situation. The S-IVB modifications identified before Christmas were being made at a snail's pace. On 21 February, Williams was told that no more money could be spent for changes until the workshop was officially approved. To fly the workshop on SA-209, approval was required immediately.[34]

Fortunately one major change to the S-IVB had already been made. Early on, von Braun had noted that the "manhole," a 71-centimeter circular opening in the forward dome, was too small to permit a suited astronaut to pass through. He was unable to find funds to make a change, however. Then in July 1965 Douglas engineers discovered cracks in welds around the manhole on stage 203; subsequent tests disclosed a structural weakness in the dome design. When it turned out that one solution was to enlarge the opening, Marshall and Douglas opted for that solution—with the workshop project in mind. The change, effective on stages 211, 507, and all subsequent S-IVBs, cost $600 000 and was financed out of Saturn funds. Von Braun also urged that the manhole cover—held on by 72 bolts—be replaced by a quick-opening hatch, but the estimate for that was $400 000, and those funds could not be found.[35] A year later, however, when Houston raised the same objection on operational grounds, the change would be quickly adopted.

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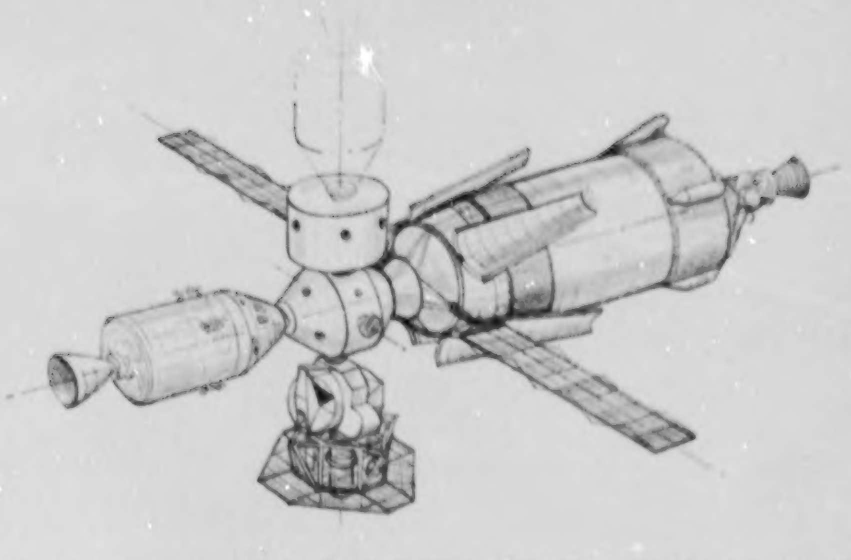
* A "command destruct system"—explosive charges detonated by radio signal—was built into the S-IVB in case the range safety officer had to destroy it in the early stages of flight.

Another troublesome question was what to do about micrometeoroids—those tiny particles, no more than one or two millimeters in size, that speed through space at enormous velocities. Three Pegasus satellites, payloads on the last three Saturn I flights, were in earth orbit measuring the number and penetrating power of these particles. The information they were sending back indicated a small but not negligible chance that the S-IVB would be struck by a micrometeoroid. To assess possible damage, Marshall arranged for tests at the Air Force's Arnold Engineering Development Center at Tullahoma, Tennessee, which had facilities for producing high-speed projectiles. Results of preliminary tests on S-IVB skin and insulation, reported in February 1966, were worrisome: micrometeoroids penetrating the metal skin could ignite the polyurethane insulation. Two solutions came to mind: an external shield to reduce the velocity of impact, or a coating on the insulation to retard the spread of combustion. A quick look at probable costs sent the engineers in search of a coating. Tests began immediately and continued for the rest of the year.[36]

Late in November Douglas was testing one coating, MSC was recommending another, and Marshall was reviewing the whole problem. Both Marshall and the contractor were reevaluating the risk of micrometeoroid damage and getting different answers. Depending on the data used, the chance the workshop would be penetrated in a 30-day mission was calculated by Douglas to be as high as 1 in 3 or as low as 1 in 40. Marshall's own estimate was 1 in 50. Douglas engineers were beginning to think about an external shield; according to their study, this would reduce the chance to 1 in 200.[37]

The fire hazard was also a function of the pressure of oxygen in the workshop's atmosphere, which was primarily a medical question. A medical staff paper prepared for Mueller in December 1966 recommended an atmosphere of 69% oxygen and 31% nitrogen, at a total pressure one-third that at sea level, for long-duration missions, but indicated that other compositions were acceptable. Marshall engineers then analyzed the micrometeoroid problem taking into account the composition of the atmosphere, and concluded that there was a net advantage in using a mixture less rich in oxygen at a pressure half that at sea level—plus the addition of an external shield. The question remained unresolved for two more months.[38]

In September 1966, MSC, having begun to examine the workshop mission in some detail, objected to the plan for activating the workshop. As it then stood, that plan required two suited astronauts to remove the



An early cluster concept sketched by Willard M. Taub, Manned Spacecraft Center. The spent S-IVB workshop is at the right. The Apollo telescope mount is attached below the multiple docking adapter, and an experiment module above. Solar cell arrays provide the power.

72 bolts from the forward tank dome cover. Experience on three Gemini missions had shown Houston that extravehicular activity was not to be taken lightly. In zero-g simulations, two men took six hours to remove the bolts, an intolerable work load. Von Braun's foresight was confirmed, but this time money was found to have Douglas design and manufacture a full-scale operating model of a quick-opening hatch for evaluation and to provide cost and schedule estimates so the decision could be made as quickly as possible.[39]

All these changes, however, were impeded by lack of money. NASA's fiscal 1967 budget request had been slashed by the budget bureau, and Apollo Applications finally received only $42 million, just enough to maintain the program at survival level.* Until well into 1967 the actual development of the orbital workshop remained pretty much where it was in mid-1966.

THE CLUSTER CONCEPT

Parallel to the efforts to define the workshop, the Office of Space Science and Applications (OSSA) was developing a major scientific project that would cause a major change in Apollo Applications. Called the Apollo telescope mount, this would be the first astronomical facility to use man as an in-orbit observer.* One of its major purposes, in fact, was to determine how useful a man could be at the controls of a sophisticated set of instruments in orbit.[40] As things turned out, the telescope mount would assume considerable scientific importance as well: it would be the only set of instruments with a chance to collect data on the sun during the next period of maximum solar activity, expected in 1969–1970.

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* See chap. 3 for Apollo Applications' fiscal problems in 1966.

OSSA's head, Homer Newell, began talks with George Mueller early in 1966 about working the Apollo telescope mount into the Apollo Applications Program. They agreed on the merits of the project, but differed about where it should be carried. OSSA planned to install it in the experiments bay of the Apollo service module, while OMSF intended to use a modified lunar module to carry bulky experiments like the telescope mount. At the end of August, Deputy Administrator Robert Seamans authorized the project and opted for Mueller's proposal.[41]

There were both technical and management difficulties in working the telescope mount into a manned spacecraft. An elaborate and costly stabilization system seemed necessary to counteract the unavoidable motion of crewmen, which would disturb the instruments' alignment. Effluents from the spacecraft could create a cloud of contamination in the vicinity of the telescopes, interfering with observations and possibly depositing material on delicate optical surfaces, degrading the results. MSC disliked using the lunar module as an experiments carrier, particularly since Mueller wanted Marshall to integrate the telescope mount with the spacecraft.[42] Houston told Mueller it could not support this idea, but he persisted; on paper, at least, the lunar module–Apollo telescope mount combination was the official configuration for three years.

Mission plans coming out of Headquarters as early as March 1966 included solar astronomy flights both as single-purpose missions and as part of long-duration workshop flights. As the months passed and some of the problems associated with the lunar module became apparent, Mueller began to see advantages in operating the telescopes from the workshop. The lunar module's systems were not designed to sustain it as a free-flying spacecraft for 28 days. Besides, Houston was dead set against flying it independently in earth orbit; if it became disabled, rescue would be extremely difficult, and reentry in a lunar module was impossible. It had no heat shield. The problems were given a thorough going-over at a briefing for Mueller at Huntsville on 19 August. At the end of the day he suggested that the observatory module might be operated while tethered to the workshop, drawing power, coolant, and oxygen through an umbilical. Marshall ran a quick feasibility study and reported the results to Management Council on 7 October, but the idea seemed to create as many problems as it solved and it gained no real support. Still, for several months Mueller kept it as a backup concept.[43]

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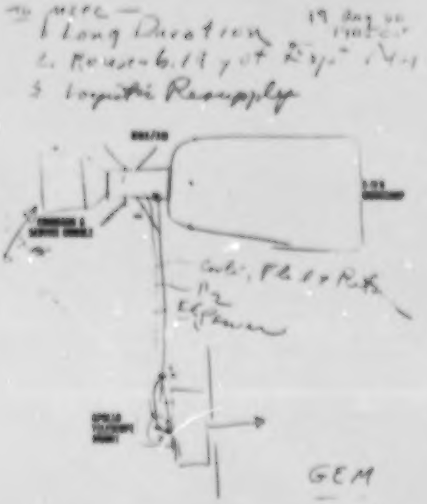
* Development of the Apollo telescope mount is treated in chap. 4.

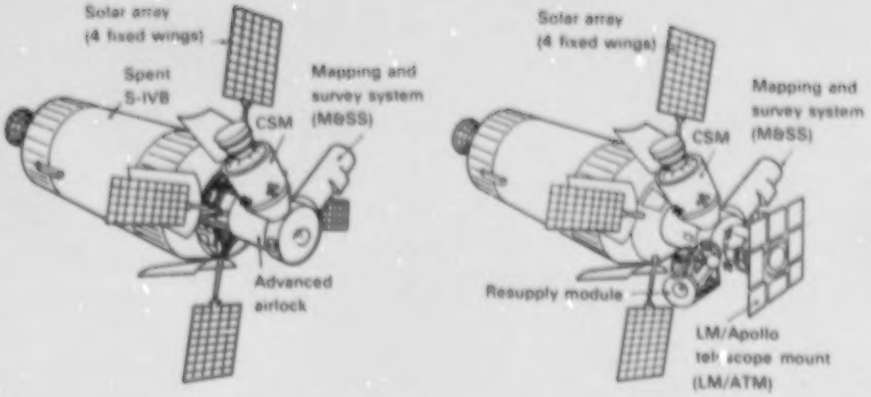


A sketch by Associate Administrator for Manned Space Flight George E. Mueller indicates his thinking on the configuration of the S-IVB workshop in August 1966.

After the October meeting it seemed that the only solution was to provide a way for the telescope module to dock with the workshop. Back in May, while the airlock studies were in progress, Mueller and the Headquarters staff had agreed that the airlock must be kept simple and inexpensive, and they had specifically ruled out double docking;[44] now that appeared to be necessary. But with the airlock contract negotiations completed, it was too late to change the design without losing several months and possibly having to go through another competition.

The only answer was to manufacture a new piece of hardware. It could be very simple: all that was needed was a shell—a cylindrical extension of the airlock—capable of withstanding launch and docking loads, but serving no purpose other than to provide two or more docking ports. It was literally a multiple docking adapter, a name that was soon made official. The details of its design changed several times during its first few weeks, but the basic idea was a cylinder, to be mounted above the airlock, carrying four radial tunnels at its upper end. The main structure and each radial tunnel would carry Apollo docking gear. The new module would have no active systems; power required at the docking ports would come from the airlock.

With the addition of the multiple docking adapter to the workshop and airlock, the nature of Apollo Applications missions was fundamentally changed. Planners began to speak of the "orbital cluster" as a core that could sustain a variety of missions. Multiple docking allowed the attachment of one or more specialized mission modules and permitted resupply for very long missions. Crews could be rotated without closing down the workshop. If a spacecraft became disabled, rescue was possible. With the birth of the cluster concept, what had been a simple experiment to use empty rocket stages looked a great deal like a small space station.



Two airlock mission configurations sketched by Wade W. Wilkerson of McDonnell Aircraft Corp., 22 December 1966.

By November, George Mueller had decided to present the orbital cluster as OMSF's main post-Apollo plan when he discussed future programs with Webb and the Director of the Budget. He felt that he had a coherent program that could be clearly defined for planning purposes and that he could now campaign vigorously for funds.[45]

One thing that still had to be done was to design the multiple docking adapter. Originally it had been intended to let Marshall fabricate the docking adapter, but the module's interface with the airlock justified asking McDonnell and MSC to see if they could do it equally well and equally cheaply. McDonnell drew up a $9-million design that Marshall considered "rather sophisticated [and] 'unsellable'"; Marshall, in turn, modified its own design so that the adapter had room to carry experiment equipment into orbit. Experiments were being considered that could not be put into the workshop before launch. In the end, Houston's design was similar to Huntsville's, but it involved a number of substantial changes to the airlock, which would cost $21.8 million and delay delivery by six months. Before the month was out, Headquarters had assigned responsibility for the multiple docking adapter to Marshall.[46]

All of the mission plans made earlier in the year were now obsolete. At the end of 1966, the Apollo Applications Program Office issued program directive 3A, based on the cluster concept, defining the first four missions. The first two launches would set up the cluster, determine the feasibility of the workshop concept, and extend man's time in space to 28 days. The third and fourth would revisit the workshop and bring up the Apollo telescope mount to gather data on the sun. A first launch in 1968 was still contemplated, but the schedule had slipped three months. After a year and a half, however, George Mueller had a program and perhaps a little breathing room.[47]

3

Apollo Applications: "Wednesday's Child"

While von Braun's engineers dealt with the technical problems of the S-IVB workshop, Mueller and his Headquarters staff applied themselves to planning and funding problems. They had much to encourage them in the summer of 1965. Edward White had capped the second manned Gemini mission in June with a spectacular space walk, rekindling public interest. Progress in the Apollo program was equally satisfying: the last three Saturn Is were launched in less than six months, and work moved along rapidly toward the first Apollo-Saturn IB flight in early 1966. Even the Soviet advances during the previous year had their bright side. The three-man *Voskhod 1* mission the previous October and Aleksei Leonov's excursion outside *Voskhod 2* in March helped NASA's budget through the executive branch and Congress with only minor reductions. The agency's appropriation for fiscal 1966 would keep Gemini and Apollo on schedule.[1]

But there were portents of trouble as well. America's involvement in Vietnam increased sharply in 1965; as the U.S. assumed a combat role, troop commitments rose from 23 000 to 184 000. At home, the Watts riot in August revealed deep-seated unrest among urban blacks. That summer President Johnson announced his intent to stay within a $100 billion budget while funding the new Medicare and War on Poverty programs. His Great Society put budgetary pressures on established programs, including the space effort. Apollo Applications became an early casualty when the White House declined to support it adequately in fiscal 1967. While the shortage of money was a principal reason, administration critics considered AAP overly ambitious and ill-conceived. Mueller was undeterred, and his faith seemed to be confirmed when Johnson expressed firm support for a large post-Apollo program in the fiscal 1968 budget.[2]

INITIAL PLANS AND BUDGETS

The Apollo Applications Program Office started off on the run with a detailed planning guideline for the manned spaceflight centers. The first flight schedule, one of hundreds to be cranked out over the next four years, called for 13 Saturn IB and 16 Saturn V flights. Four of the missions were scheduled to fly excess hardware from the lunar landing program; the remaining 25 represented new Saturn-Apollo purchases. The missions fell into four categories (earth orbital, synchronous, lunar orbital, and lunar surface) and two phases. The first 8 missions would employ a standard Apollo command-service module for 14-day flights; on later missions an extended Apollo would allow flights of 45 days.[3]

A major new challenge was the integration of experiment payloads. Integration entailed fitting the spacecraft and experiment hardware together—ensuring the two were compatible mechanically, electrically, and in all other ways. It also involved grouping experiments so that the operation of one would not distort another's results. The program office divided payload integration between the two manned spaceflight centers at Houston and Huntsville. Houston handled all experiments in the Apollo command-service module, the biomedical-behavioral experiments relating to the astronauts, and experiments for advanced spacecraft subsystems. Lunar surface work, astronomy-astrophysics, and the physical sciences went to Huntsville. The flight schedule gave Houston primary responsibility for 17 missions, including the initial flight that focused on earth resources. Marshall would integrate 12 mission payloads, among them the final 2 flights destined for lunar exploration.[4]

With planning guidelines on their way to the field centers, the Headquarters staff turned to briefings for the congressional space committees. During the previous year, several congressmen had expressed concern about the future of America's space programs. The space committees, chaired by Sen. Clinton Anderson and Rep. George Miller, were well disposed toward NASA's programs and realized that unless a new manned program started in 1966, NASA faced a period of inactivity after the lunar landing. The chairmen publicized NASA's plans and boosted them if possible. Their concern coincided with George Mueller's. Facing a tough battle in getting his AAP budget request through the Johnson administration, Mueller needed all the congressional support that he could muster.[5]

On 23 August, Mueller gave Anderson's committee a broad view of program objectives, experiments, and proposed flight hardware. The testimony indicated a change of emphasis. Whereas NASA officials had previously played up the technological aspects of earth-orbital operations, AAP placed more attention on space science. The AAP office had identified 150 experiments, grouped by general field of interest and experiment area. Nearly half that number were classified as "space science/applications," including 24 medical experiments to test the physiological effects of extended stays in space. The scientific community's interest in the moon accounted for 35 lunar-surface experiments.*[6]

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* Until Dec. 1967, when a Lunar Explorations office was established under Apollo, lunar exploration was assigned to AAP.

The hearings revealed differences among NASA's leaders regarding the scope of AAP. Mueller was eager to push ahead with the program, envisioning 29 flights between 1968 and 1971; Webb and Seamans spoke more of AAP as an interim program for the early 1970s. Mueller's plan called for an annual production and launch of 6 Saturn IBs, 6 Saturn Vs, and 8 Apollos; Webb and Seamans seemed less concerned about the exact numbers. According to Mueller, the differences represented an attempt by his superiors to play down the costs. Other NASA officials have suggested that Mueller's enthusiasm for AAP far exceeded his bosses'.[7]

Although the presentations to the two committees were well organized, AAP obviously needed more work. NASA's systematic approach to increased flight times was missing. The agency's rule of thumb had been to double the longest previous flight when testing man's endurance in space, but AAP's 14- and 45-day missions were set by hardware constraints rather than medical considerations. AAP's experiment package resembled a long shopping list. The House staff report noted that only three of the experiments had actually been assigned to the program. The report criticized NASA on other counts: "At no time did any NASA witness say how much the Apollo Applications program would cost, nor did any witness define the parameters of the program or set out exactly what the program would seek to accomplish." The criticism was not entirely justified, since Mueller had told the Senate group that parameters and costs for AAP would be established during the project definition phase; AAP was not an "approved" program, although he hoped for a decision soon.[8]

In the FY 1967 budget request, NASA's preliminary estimates for a full-scale AAP program totaled $450 million, with over $1 billion being required the following year. Bureau of the Budget officials, thinking in terms of $100 million for AAP in FY 1967, were taken aback. They agreed, however, to listen to arguments for $250 million. Mueller considered the compromise figure insufficient and set out to increase it. His first task was winning over NASA's top administrators. To do so, Mueller marshaled five arguments:

1. If Gemini had given America any advantage in the space race, it was slim at best and could disappear if funding was inadequate.
2. The scientific and technological communities, in conjunction with NASA, had identified several hundred experiments for AAP; a $450 million program would include only half of what was needed for 150 of the most promising.
3. While the esprit de corps of NASA's manned spaceflight team was well known, a slowdown in the program would lower morale.
4. The Bureau of the Budget's proposal represented poor economic policy since it would cause significant unemployment and leave

America's Apollo investment largely unused from 1968 through 1971.

5. It also represented poor political strategy. The resulting unemployment and misuse of the Apollo investment could become a political issue in 1968.[9]

The arguments failed to convince Seamans. On 15 September he recommended a $250 million budget; Webb subsequently concurred.*

If that battle ended in a draw, a more difficult one lay ahead: getting the $250 million request through the Bureau of the Budget. Work on several program options during the next few weeks would ultimately prove to be an exercise in futility. In November, NASA presented the Budget Bureau with two funding levels for FY 1967: a desired $5.76 billion and a minimum of $5.25 billion. The bureau countered with $5.1 billion, slightly below the agency's FY 1966 appropriation. Budget officials reduced manned spaceflight's share by $222 million; and since Apollo was inviolable, AAP absorbed the loss. Webb appealed the decision at the LBJ ranch in December but to no avail. In the administration's final budget request, NASA's $5.012 billion included $42 million for AAP—just enough to keep some options open.[10]

SEEKING NEW JUSTIFICATION

The Budget Bureau's lack of enthusiasm for AAP was shared by the Senate space committee. On 27 January 1966 Senator Anderson told Administrator Webb his committee saw merit in building a post-Apollo program around a major new goal rather than "loosely related scientific experiments.' They were concerned that the extended use of Apollo hardware might stunt the growth of new technology. Because many AAP goals might be attained earlier by DoD's Manned Orbiting Laboratory, he urged close coordination with the Air Force. Given the likelihood of excess Apollo hardware, the committee supported initial planning and experiment work, but would not fund additional launch vehicles and spacecraft. "The Committee expects additional justification and specific recommendations for the Apollo Applications Program if such a program is to proceed."[11]

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* AAP's early funding is a confusing matter. Since it was not a recognized program, the initial work came under Advanced Missions and subsequently Apollo Mission Support. A separate AAP line item did not appear until FY 1968. In addition to the appropriations for AAP ($26 million in FY 1966 and eventually $71 million in FY 1967), experiment funds also came out of OSSA and OART. NASA's operating budget for FY 1966 showed $51.2 million for AAP, including $40 million for experiments and $8.5 million for space vehicles. AAP's share of the FY 1967 operating budget increased to $80 million, of which $38.6 million went to vehicle hardware and $35.6 million to experiments. NASA Budget Briefings for FY 1966 through FY 1968.

Having anticipated attacks on AAP objectives, Mueller turned to members of the immediate Apollo family for help. He asked senior managers from the major Apollo contractors to evaluate five AAP goals:

1. Explore and utilize world resources for the benefit of mankind;
2. Define and develop the operational capabilities for the next generation of space vehicles beyond the Saturn-Apollo systems;
3. Expand man's knowledge of the near-earth and lunar environments;
4. Increase the security of the United States through space operations;
5. Develop a capability to provide a livable, usable environment for man to operate effectively in space for one year.

The executives generally favored the first goal because of its public appeal, but saw serious difficulties in implementing such a program. One responded, "A laudable objective but we do not know how to do it. Beyond the purview of MSF." Most feared that goal four would confuse the American public as to the roles of NASA and DoD. While the other objectives drew varying levels of support, no consensus emerged. Mueller concluded that, "just as there is no 'average U.S. citizen,' there also appears to be no 'average Apollo executive.'"[12]

In the February 1966 issue of *Astronautics and Aeronautics*, columnist Henry Simmons likened the floundering Apollo Applications Program to Wednesday's child, "full of woe." He acknowledged as sound the reasons for an ambitious program: the need to keep the Apollo organization intact and secure an adequate return from the huge Apollo investment. FY 1967 budget cuts suggested, however, that NASA might have to accept a smaller program, limited to the hardware left over from the lunar landing. The development of sophisticated experiments and the procurement of additional Saturns and Apollos seemed unlikely. According to Simmons, space scientists were particularly unhappy with AAP, considering many of its experiments "make-work." Deferral of AAP funding had probably prevented an "outright rebellion in the scientific community, and possibly an internal explosion within NASA as well." Simmons faulted AAP on two counts: NASA's failure to measure the worth of manned versus unmanned space science; and, if manned flights were "cost-effective," the agency's reluctance to fly earth-orbital missions on the Manned Orbiting Laboratory. Nevertheless, Simmons concluded that NASA had no alternative but to press on with AAP in some form. Otherwise, its Apollo team would scatter to the four winds.[13]

AAP's future looked no better from inside NASA, where key officials held serious reservations. Simmons's reference to a possible "internal explosion" probably overstated the case, but there was considerable resentment of AAP in the Office of Space Science and Applications. There was also strong opposition to the program within the manned spaceflight family, most of it emanating from Houston. MSC officials had questioned basic aspects of AAP since its inception and, during the winter of 1965–1966, voiced their objections on several occasions. In March 1966, Robert Gilruth formalized his center's opposition in an eight-page letter to Mueller.

Gilruth agreed with the basic intent of AAP: the continued use of Apollo to conduct scientific work in earth orbit and on the moon. NASA had failed, however, to tie the program to a "definite goal or direction for the future of manned space flight." MSC considered that the unrealistically high launch rate being planned was dictating "that we select missions and experiments that *can* be done by a certain time, rather than those that *should* be done." As a result, space technology was not being advanced. AAP's timing and content should therefore be oriented more toward NASA's next major program after Apollo.[14]

Houston strongly opposed AAP's proposed modifications to Apollo hardware. In particular, changing the lunar module upset center engineers. They considered its interior unsuitable as either a laboratory or a lunar shelter. Converting the lunar module to a space laboratory involved the removal of many subsystems and the installation of new ones for which it had not been designed. Gilruth concluded that the proposed uses of the lunar module "represent modification of the very expensive special-purpose vehicle for use in places where another module would be more suitable." Gilruth considered AAP a possible detriment to the Apollo program. Support of the proposed launch rate would require additional trainers, simulators, and operational equipment. Since little AAP money was available, Gilruth feared the possible use of Apollo funds. Already the many changes in AAP plans, caused mainly by the lack of funding, had diverted management's attention.[15]

Having laid out Houston's objections to AAP, Gilruth proposed an alternative. NASA should define its manned spaceflight goals for the next two decades; he recommended a permanent, manned orbital station and a planetary spacecraft. AAP could then be organized in support of these goals, and Apollo hardware used for tasks that involved no redesign. He noted that his recommendations were more in line with available funds. Gilruth's closing remarks summed up NASA's dilemma in early 1966:

> These recommendations are prompted by a deep concern that at this time a critical mismatch exists between the present AAP planning, the significant opportunities for manned space flight, and the resources available for this program. . . . AAP, as now constrained, will do little more than maintain the rate of production and flights of Apollo hardware. Merely doing this, without planning for a major program, and without doing significant research and development as part of AAP, will not maintain the momentum we have achieved in the manned space flight program.[16]

Mueller's response is not recorded. However, subsequent AAP developments show little impact from Gilruth's letter. The program office pursued a course generally antithetical to MSC's views, and Houston would raise objections on subsequent occasions.

AAP vs. MOL

Mueller's efforts to groom AAP as Apollo's heir were jeopardized by claims of the rival Manned Orbiting Laboratory (pp. 15–19). Although NASA officials spoke of the two as unrelated programs, members of Congress and the executive branch considered them competitors. In fact, NASA and the Air Force supported each other at a technical level, while competing for political support. The programs interacted in a number of ways: Houston provided support to the Gemini portion of MOL, NASA and Air Force personnel worked together on joint panels and coordinated experiments of mutual interest, and each agency lent key officials to the other. In shaping its post-Apollo plans, NASA gave frequent consideration to MOL's merits; Webb and other agency officials displayed a surprising objectivity toward NASA's use of MOL. It was difficult, however, for the Office of Manned Space Flight to view the Air Force program with charity. AAP and MOL were vying for limited space funds, and it was unlikely that both would survive. AAP might have fared no better in MOL's absence, but the competition seemed financially detrimental.[17]

Presidential approval of MOL in August 1965 proved less a boon than expected, and the Air Force's Space Systems Division continued to want for money. By the fall of 1965, the launch vehicle for MOL had been selected: a Titan IIIC with strap-on solid-fuel boosters. At the same time a launch complex at the Western Test Range in California was designed. In November Air Force officers prepared a position paper on the proposed expansion of the Satellite Control Facility at Sunnyvale, California, a move opposed by congressional critics who thought the military should use Houston's mission-control center. Shortly after the new year, bulldozers began clearing ground for the launch facility at Vandenberg AFB. By June 1966 the long-lead-time items for the launch vehicle were on order.[18]

Before August 1965, NASA and DoD had worked out matters of common interest through ad hoc groups or through the Aeronautics and Astronautics Coordinating Board and its panels. MOL's approval prompted new arrangements to handle the substantial increase in coordination. By mid-October Mueller and Gen. Bernard Schriever, head of Air Force Systems Command, had signed the first agreement covering experiments. During the following year, a series of joint agreements defined relationships at the working level. Coordination between top-ranking officials was assured with the creation in January 1966 of the Manned Space Flight Policy Committee. Membership included Seamans, Mueller, Newell, and their DoD counterparts. In congressional testimony, program officials maintained a common front: MOL and AAP were independent, serving unrelated but worthy goals.[19]

The NASA-DoD position failed to convince those critics in Congress and the Johnson administration who wanted to unite the two programs. On 27 January 1966, legislators from both houses took aim at the NASA program. Senator Anderson's letter to Webb that day recommended use of MOL; in the House, the Military Operations Subcommittee concluded three days of hearings on Missile Ground Operations with some caustic remarks about overlapping programs. A subsequent report called AAP "unwarranted duplication" and an unapproved program that "could cost from $1 to $2 billion a year." The subcommittee cited the support of "eminent space scientists" for a joint program and concluded that a merger would save billions of dollars. Furthermore, the military should run the show.[20]

For several years, the Budget Bureau had questioned the need for separate earth-orbiting laboratories. In discussions on the FY 1968 budget, bureau officials supported a common program, with NASA flying experiments on MOL missions or at least using the cheaper Titan III rocket. In September the President's Scientific Advisory Committee joined the chorus of critics. The committee was unhappy with the spent-stage concept; the extensive construction it required early in the mission would likely distort the medical results. Its report concluded that NASA should examine MOL closely before committing large sums to AAP.[21]

NASA's response to the criticism was twofold: it asked Douglas Aircraft to evaluate MOL's usefulness in meeting early AAP objectives, and it began a detailed in-house comparison of the two programs. The Office of Manned Space Flight's first consideration was the use of Titan for AAP. Even NASA officials admitted that the Saturn IB was an uneconomical launch vehicle; its costs per launch were roughly twice those of the Titan III. By using the Air Force rocket, NASA could save about $15 million per mission. The OMSF team found the Titan-Apollo combination technically feasible, although the payload in low orbit might drop by 10%. Far more important was the time and money needed to integrate the Titan and Apollo. OMSF estimated that systems integration, launch facility modifications, additional checkout equipment, and two qualification flights would take at least 3½ years and cost about $250 million. At that rate, use of the Titan would delay the first AAP mission by two years and require 17 launches before the savings surpassed the initial costs of conversion. Changing launch vehicles would also render useless all the work accomplished on the Saturn workshop. The telling point, however, was the large cost of combining the Titan and Apollo systems.[22]

OMSF found equally good reasons for not conducting its AAP program aboard the Air Force laboratory. The basic MOL configuration was inadequate to meet AAP goals, while a DoD proposal for a larger MOL would take four years to develop and cost an additional $480 million in facility modifications. Even then, OMSF calculated that, to achieve the same results, an uprated MOL program would cost more annually than the Saturn IB and Apollo. Armed with these figures, NASA officials, in testifying at congressional hearings, held out for an independent Apollo Applications Program.[23]

CENTER ROLES AND MISSIONS

During NASA's brief history, tasks in manned spaceflight had been clearly defined: von Braun's team in Huntsville had responsibility for launch vehicles, Robert Gilruth's engineers directed spacecraft development from Houston. The two organizations first worked together on the Mercury-Redstone flights. Gemini was largely MSC's show, with the Air Force providing the Titan launch vehicle and Houston holding the operations in close rein. Apollo was too big for one center, but its work load divided into reasonably distinct areas: Saturn launch vehicle, Apollo spacecraft, launch operations (Kennedy Space Center), and communications (Goddard Space Flight Center). Several jurisdictional disputes arose, along with scores of minor disagreements; but by and large, parochial interests were subordinated to the lunar landing.

Possibilities for conflict were more numerous with AAP. While Apollo offered something for everyone, post-Apollo appeared less promising, especially for Huntsville. There would be no successor to the Saturn V for at least a decade, and the Saturn IB would be phased out in 1968 unless AAP got under way. When Mueller seized upon the wet workshop as an inexpensive approach to long-duration flights, Marshall's future brightened perceptibly, and no doubt the center's needs had weighed heavily in Mueller's decision. The choice, however, rankled Houston officials who viewed space stations as their rightful prerogative: The wet workshop altered MSC-MSFC relations; they were now competitors as well as collaborators.[24]

In another agency, the headquarters might have dictated a division of effort; but NASA's field centers enjoyed considerable autonomy. Historically, the NACA centers had pursued their work independently. During the rapid growth of manned spaceflight in the early 1960s, OMSF lacked the manpower to supervise the centers closely. A plan to contract with General Electric Company for that purpose had been rebuffed by the field centers. In identifying U.S. space achievements with Houston, Huntsville, and the Cape, the American public strengthened the centers' position. Despite Mueller's efforts to direct the manned space program from OMSF, the centers still displayed much independence in 1965.[25]

AAP's planning guideline of August 1965 assigned integration tasks to the centers in line with Apollo duties: Houston was given spacecraft responsibilities and Huntsville the launch vehicle. After informal discussions with center representatives, Mueller amended the assignments in September. Besides developing all standard and modified spacecraft, MSC would direct astronaut training, mission control, and flight operations. In addition to its launch vehicle responsibilities, Marshall would integrate experiments into the lunar module.[26]

Since lunar-module development was under Houston's purview, the decision represented a significant step away from Apollo assignments and upset some people in Texas. On 14 October 1965 the *Houston Post* reported, "Marshall May Take 2nd Apollo Control." Quoting an OMSF spokesman, the article stated that Huntsville would integrate AAP payloads and Headquarters would probably manage the program. The *Post* acknowledged that mission control and astronaut training would remain in Houston. The article caused a minor tempest. Rep. Olin Teague, the Texas Democrat chairing NASA's oversight subcommittee, looked into the matter. Until the air cleared, OMSF officials treated the issue discreetly.[27]

Initial proposals of roles and missions were understood to be tentative. Before formalizing them—including Huntsville's responsibility for the lunar module—Mueller sought to convince Webb and Seamans that his proposals were appropriate. It was easy to demonstrate that the entire responsibility for payload integration would be too great a burden on any one center. Splitting the LM integration work between Houston and Huntsville would exceed MSC's 1968 personnel limit while leaving Marshall with excess people. Dividing the LM responsibility also resulted in duplication of mock-ups and support equipment. Placing the entire LM payload integration in Huntsville, however, would keep both centers below their personnel ceilings. Further, activity at both centers would increase under Mueller's proposal. He assured his bosses that Marshall had the proper mix of engineering skills to handle LM integration. Webb approved the division of responsibilities with one proviso: Huntsville's program office was to have the title "LM Applications" or "LM Integration Office" rather than "Apollo Applications." The administrator wanted to make clear that NASA's "manned flight program activity is not shifting its center of focus but rather that we are using effectively all our available resources."[28]

Huntsville quickly seized the opportunity, opening an Experiments and Applications Office in mid-December. In March 1966 Leland F. Belew,* MSFC's former manager for Saturn engines, became director of

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* Belew was born in Salem, Mo., in 1925. He received a B.S. in mechanical engineering from the University of Missouri-Rolla in 1950 and went to work for the Redstone Arsenal the next year. He transferred to NASA along with the Development Operations Division of the Army Ballistic Missile Agency in 1960. In 1975 he became deputy director of the Science and Engineering Directorate at MSFC.

Marshall's Saturn–AAP Office (Webb's proviso apparently being forgotten). Belew and other AAP engineers were embarked on an eight-year enterprise.[29]

Payload integration was among the first items of business. By May, Marshall had given parallel, one-year, $1-million contracts to Lockheed and the Martin Company of Denver. The contractors were to examine experiment hardware, installation and integration of equipment, crew requirements, launch facility requirements, tracking, and mission analysis. In September the two companies conducted independent reviews of OMSF plans for flights 1–4. The following month Belew enlisted Martin's aid in more detailed planning of the spent-stage mission, while Lockheed's team provided a similar service for the Apollo telescope mount missions. Huntsville had earlier considered payload integration without contractor support, but the Lockheed and Martin work convinced them otherwise. In November 1966, Marshall began preparing a work statement for an integration contract.[30]

AAP organization at Houston proceeded at a slower pace. Officials there had little enthusiasm for AAP and less for the proposed use of the lunar module. In light of Grumman's problems with the lunar landing mission, Houston considered AAP requirements an untimely diversion. Mueller's recommendation that Marshall integrate payloads into the lunar module raised few objections, but his subsequent suggestion that Marshall supervise LM modifications for AAP encountered strong opposition: it seemed to threaten MSC's responsibility for flight safety. In fact, Gilruth considered any use of the LM in AAP "so unsound technically and financially that it [could] seriously weaken the National program." Mueller, in turn, accused MSC of nonsupport. Gilruth insisted that his center was providing AAP with "a very large engineering and management effort." He argued that MSC's delay in establishing a program office had not harmed AAP; indeed, it would be difficult to set up an AAP office until Headquarters defined the program. He still believed AAP lacked specific goals.[31]

Mueller and Gilruth discussed their views frankly in mid-April, and a week later Gilruth appointed his deputy director, George Low, as Houston's "point of contact" for AAP. Houston's AAP Office opened for business on 6 July 1966. Other center duties occupied much of Low's time, however, and his deputy was left to take the lead in many AAP matters.[32]

MSC officials feared a loss of authority in areas other than the lunar module. Some saw the broad scope of Marshall's payload integration tasks as raising fundamental questions about MSC's role in mission planning and flight operations. Others feared a dilution of MSC's control of astronaut training. The latter issue led to an agreement between the two centers that astronauts would train with particular experiments during integration work at Huntsville, but that Marshall "would not in any way establish an 'Astronaut Training Center.' "[33]

Some progress was made toward settlement of the roles and missions question in early 1966 when OMSF and the two centers divided responsibility for the spent-stage mission. Huntsville would design the workshop, implementing an experiment program that incorporated items from MSC and other sources. Houston's Gemini office would direct work on the airlock module. The agreement covered only one mission, however, and disputes on other AAP roles continued to surface.[34] Mueller sought to resolve the differences at the August session of OMSF's Management Council, a three-day hideaway meeting at Lake Logan, North Carolina.

The deputy directors of the three manned spaceflight centers (Low, Eberhard Rees of Marshall, and Albert Siepert of Kennedy) started with the assumptions that a space station represented a logical goal between early AAP missions and complex planetary flights and that any space station design could be modular, with a command post, a mission module, and one or more experiment modules. The command module, providing guidance, navigation, control, and communications for the station, would be developed by MSC. MSFC would be responsible for the mission module in which the crew lived, slept, and performed some experiments. Both centers would work on experiment modules. The Lake Logan accord applied the space-station model to AAP, defining the Apollo command-service module and airlock module* as a command post, the orbital workshop as a mission module, and the Apollo telescope mount as an experiment module under Marshall's direction. Although the agreement gave Huntsville the primary role in early AAP launches, it reaffirmed Houston's responsibility for flight operations, astronaut activities, life-support systems, and medical research.[35]

Gilruth and von Braun signed the Lake Logan agreement in late August, but the *Houston Post* continued to hold out. On 10 October a front-page article by Jim Maloney was headed, "Von Braun a Persuasive Voice—Some MSC Tasks Being Moved." While praising Huntsville's rocket work, Maloney viewed the payload integration and Apollo telescope mount assignments as encroachments on Houston's spacecraft role. "Where are those who should argue that you can't break up the group that developed the Mercury, Gemini, and Apollo and should develop the spacecraft for Mars and beyond?" The *Post* article brought new congressional inquiries for Mueller to answer. His response, focusing on the August agreement, apparently satisfied NASA's congressional committees, but not Maloney, who in subsequent articles attacked the spent-stage mission through unidentified MSC sources and accused the center leaders of kowtowing to headquarters. Maloney overstated the problem, but his fears were shared by some engineers. The Lake Logan agreement was a convenient formula, but did not eliminate the competition between centers for post-Apollo work.[36]

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* In the next 18 months, the workload at MSC increased, while that at Marshall declined. When Headquarters proposed to move the airlock contract to MSFC, Gilruth agreed and added that MSFC should also manage systems engineering for the entire cluster, including the lunar module (by that time manned rendezvous with the LM had been dropped). He even offered to provide MSFC with formal training in crew systems. Gilruth to Mathews, "Proposed Management Responsibilities—Apollo Applications Program," 29 Mar. 1968. Someone annotated the file copy in the Houston AAP office: "the giveaway."

Presidential Approval

The Johnson administration had deferred decision on AAP in 1965, hoping for better times the following year. Instead, matters grew worse. Troop strength in Vietnam increased from 184 000 to 385 000 and the costs of war soared from $6 billion to $20 billion. President Johnson believed that he could defend U.S. interests in Southeast Asia without sacrificing Great Society programs—as critics said, that he could have both guns and butter. Many congressmen disagreed, however, and landslide Republican victories in 1966 indicated widespread dissatisfaction.[37]

Johnson's troubles were to a large extent NASA's, a fact readily appreciated by James Webb. At a management review shortly after the election, Webb spoke about the hard times. Space programs were under increasing attack, the critics focusing on Apollo's size and the possibility of large post-Apollo programs. At the Bureau of the Budget, officials were pressing Webb to eliminate the last five Saturn Vs from the Apollo program. The bureau had little enthusiasm for AAP, and Webb doubted that the administration or Congress would approve the program until NASA established definite goals for it. Webb admonished his managers not to push Apollo-Saturn hardware, but to emphasize national needs that could be met with the Apollo capability. Internal considerations such as NASA's desire to keep the Apollo team in business were important, but should be left out of the sales pitch. He warned against center parochialism. Continued divisiveness within the agency could seriously harm post-Apollo programs. He urged his associates not to underestimate the severe conditions facing AAP.[38]

AAP appeared much healthier by mid-December, at least to George Mueller. In a meeting of OMSF staff and center representatives, Mueller acknowledged that a few months earlier most outsiders had viewed AAP as "little more than a bill of goodies," and there had been serious doubts about man's role in space science. At August briefings, neither the Budget Bureau nor the president's scientific advisers had shown interest in a post-Apollo program. Since then, however, Webb's emphasis on the workshop cluster as a low-cost means of long-duration flight and effective science (particularly solar astronomy with the telescope mount) had improved AAP's standing with the administration.[39]

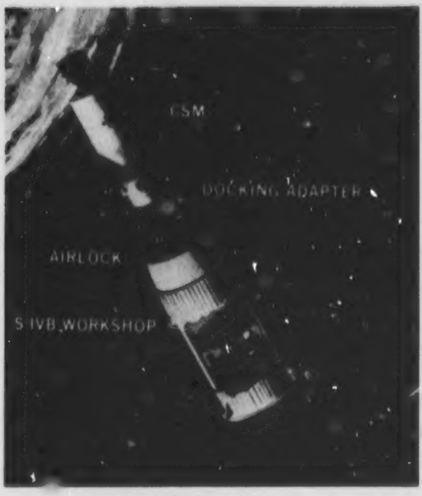
The best evidence for that new standing lay in NASA's FY 1968 budget proposal for AAP. Several aspects of the program still troubled Budget Bureau officials: its lack of clear goals, possible duplication with the Air Force's Manned Orbiting Laboratory, the merits of manned versus unmanned missions for space science, and the timing of AAP flights and Apollo missions; but the administration was not looking to end manned spaceflight. After lengthy debate, NASA's AAP request had been pared from $626 million to $454 million. While the reduction meant a slowdown, the figure represented the first large sum set aside for AAP. More important, the decision reflected Lyndon Johnson's formal commitment to AAP. As his budget message said, "We have no alternative unless we wish to abandon the manned space capability we have created."[40]

During the mid-1960s, AAP was frequently described as a bridge between Apollo and NASA's next major manned program. When President Johnson approved AAP in a time of severe funding problems, it became a bridge over troubled waters. For 18 months the AAP office had struggled for recognition. The program had first been deferred and then scaled downward. By August 1966 supporters had feared for its life. Following Johnson's approval, there again seemed to be a reasonable chance of success. (Mueller remained the optimist: AAP's 1966 schedule called for 37 flights through 1973 at a cost of $7 billion.) Still needed was firm public and congressional support. A major opportunity to get it came with the release of the budget message in January 1967.[41]

Robert Seamans sketched the outlines of AAP funding at NASA's FY 1968 budget briefing on the 23d. NASA was seeking $263.7 million for additional Saturn-Apollo hardware (four Saturn IBs and four Saturn Vs per year), $140.7 million to cover experiments, and $50.3 million for mission support. The amount for mission support pointed up the short time remaining before the first AAP mission in June 1968. In the question-and-answer period, Mueller provided further details. NASA planned to launch its orbital workshop in mid-1968 and follow with a solar observatory (the telescope mount) six months later. Revisits to the workshop would come in 1969. Administrator Webb emphasized the latter point: "This budget makes the transition from the time when we had to count on sending up things, and using them once, to where we expect basically to park large systems in orbit and go back and use them time after time."[42] AAP had been sold to the president largely from this standpoint.

Press representatives asked for a more detailed presentation on AAP, and Mueller obliged on 26 January. AAP plans showed considerable maturity, compared to a presentation in August 1965. The earlier schedule had seemed a loose collection of individual missions, filling the gap between Apollo and the next major program. In the intervening 18 months, the orbital cluster had become a focal point for program activities

AAP 1 & 2, Orbital Configuration, a briefing chart used at NASA Headquarters in March 1967. ML67-6426.



and a test bed for future space stations. During the briefing, Mueller referred to the cluster as an embryonic space station.[43]

Mueller concentrated on the four AAP flights that were considered firm. The first mission consisted of two launches: an Apollo command-service module followed by the workshop, airlock, and multiple docking adapter. The workshop would remain in a 510-kilometer orbit for at least three years. After linking their spacecraft with the docking adapter, astronauts would occupy the spent stage for 28 days, twice the length of the longest Gemini flight. Four days were allotted for construction of the rudimentary two-story workshop in the spent S-IVB stage. The bottom floor would serve as living quarters, with fabric curtains separating areas for sleeping, food preparation, waste management, and exercise. Similar partitions would divide work stations on the upper level. The airlock, under development by McDonnell Corporation, would provide the oxygen and nitrogen for a shirtsleeve atmosphere, electrical power, and most of the expendables for the 28-day mission. The newsmen seemed impressed by the size of the workshop, perhaps mentally contrasting it with the narrow confines of Gemini and Apollo. One reporter asked if the workshop equaled the space of an average ranch house. Mueller replied: "A small ranch house. The kind I can afford to buy."[44]

Medical concerns headed the list of experiments on the first mission. Physiological tests included a vectorcardiogram and studies of metabolic activity, bone and muscle changes, and the vestibular function. The crew would also conduct 18 engineering and technology experiments, ranging from a test of jet shoes to an investigation of how materials burned in space. The jet shoes, developed at Langley Research Center, resembled skates with gas jets attached. In the closed confines of the workshop, astronauts could safely evaluate their use as maneuvering aids for future extravehicular activity. Since this would be the first of many lengthy flights, several experiments evaluated aspects of crew comfort such as sleeping arrangements, getting in and out of suits, and the habitability of the workshop.[45]

Three to six months after the first mission, the second would be launched for a 56-day stay in orbit. One Saturn IB would carry a manned Apollo plus a supply module. Another would lift the telescope mount. By any measure, the solar apparatus was complex. The telescope canister measured two meters in diameter by nearly four meters in length and weighed a ton; it housed a dozen delicate instruments.* For most observations, the telescope mount would be attached to the workshop; but under certain conditions, the crew might tether it a short distance from the cluster. Normal operations would require one astronaut; the other crewmen would eat, sleep, or perform other experiments. Mueller described the package as "the most comprehensive array of instruments that has ever been assembled for observing the Sun." NASA hoped to have it in operation by early 1969 when sunspot activity peaked.[46]

Although plans beyond the first two missions were indefinite, Mueller briefly reviewed the total program. Four crews would visit the cluster in 1969 to conduct new experiments and more solar observations. Specific experiments for these flights were as yet undefined, but likely payloads included earth-resource cameras and weather instruments. In 1970 NASA would launch a second Saturn IB workshop, followed by another telescope mount in January 1971. Through resupply and crew-transfer flights, NASA hoped to achieve a year-long mission by 1971. Plans to monitor the effects of space included a 1970 launch of an Apollo biomedical laboratory. The first lunar-mapping flight was set for December 1969; two-week visits to the moon would follow in 1971. Anticipating large logistical requirements, planners were scheduling two Saturn V launches for each extended mission on the moon. (Much of the equipment later used for Apollo lunar exploration, such as the rover, was under consideration for AAP.) In late 1971 NASA would launch the first of two Saturn V workshops. Four Apollo flights were programmed to visit each of these laboratories. It was, as a NASA official noted, "quite an ambitious program."[47]

During FY 1967 and FY 1968, the AAP Office expected to initiate seven major projects: the airlock and workshop, the telescope mount, a lunar mapping and survey system, Apollo modifications for long-duration flights, a lunar shelter based on the lunar module, experiment payloads, and an Apollo land-landing capability. The last project would permit the reuse of Apollo spacecraft, thereby supplementing the savings of workshop revisits. Three years earlier, Houston had ruled out land recovery for Apollo because the problems of braking the craft's descent had outweighed its advantages. The AAP Office believed the land-landing feature worthwhile, however; besides permitting reuse, it would allow the Apollo to carry six men. In a soft landing, astronauts' couches would require less space to absorb shock.[48]

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* The telescope mount will be described in detail in the next chapter.

The positive tone of the presentation was, perhaps, more important than the content. What George Mueller had sought for 18 months seemed now within his grasp. But events would prove otherwise—the next two years would confirm that AAP was, indeed, Wednesday's child.

4

A Science Program for Manned Spaceflight

In his press briefing on 26 January 1967, George Mueller described an Apollo Applications Program with a large scientific component. Most of that scientific work had been defined only in the preceding year; late in 1965, Marshall Space Flight Center's space science director had noted to von Braun, "The list of scientific experiments available for early AAP flights is remarkably short."[1] Although NASA had assembled a long list of scientific studies for an earth-orbiting laboratory (pp. 18, 77), only three experiments* were actually under development.

Considering the tenuous state of AAP at the time, that was hardly surprising. But since AAP missions would use hardware that was already moving into production, while scientific projects existed mostly on paper, experiments demanded attention—especially after Mueller ordered acceleration of the orbital workshop project in December 1965. Early in 1966 Headquarters began canvassing the field centers for experiments that had been developed enough to be flown early at minimum additional cost.

The fact was that experiments were new to manned spaceflight. The Office of Manned Space Flight and its field centers, loaded with Saturn and Apollo work, had little time to give to peripheral concerns, while the Office of Space Science had only recently worked up real interest in the manned program. The two offices would have to learn to work together; and because they had different histories, objectives, and approaches to their work, there would be some lost motion while they learned.

SCIENCE IN SPACE TO 1965

In the U.S., scientific research in space began with the postwar V-2 flights and continued with orbiting satellites, the first of which (*Ex-*

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* *Experiment*, as NASA uses the term, refers to any exercise whose purpose is to gather scientific or engineering data, and also to the equipment used for that purpose.

plorer 1) went into orbit on 31 January 1958. Under the auspices of NASA's Office of Space Sciences (OSS), researchers in astronomy and space physics gathered vast quantities of data and designed increasingly sophisticated instruments to push the frontiers of knowledge still further.[2] NASA's Office of Applications moved forward with communications, navigation, and weather satellites. From 1963 to 1971 the two offices were combined as the Office of Space Science and Applications (OSSA), which by 1965 had a well organized program encompassing launch vehicles, a tracking and data-acquisition network, a center responsible for science and applications programs (Goddard Space Flight Center, Greenbelt, Md.), and a clientele of scientists. OSSA also supported university research programs and provided research fellowships for individual graduate students. By FY 1965 this support had reached a level of $46 million—small compared to what some agencies spent on research, but nonetheless significant to the academic community.[3]

The chief of OSS and later OSSA was Homer E. Newell, who came to NASA in 1958 from the U.S. Naval Research Laboratory, where he had been coordinator of the science program for the Vanguard satellite project. A mathematics Ph.D., Newell had investigated radio propagation and upper-air phenomena before becoming involved in satellite work. In 1961 he was appointed director of the Office of Space Sciences, responsible for all of the space agency's science programs.*[4]

In that position Newell had to balance the appetite of scientists for research support against the funds provided by a generally practical-minded Congress. Space research, though it had a long jump on manned spaceflight, was neither as glamorous as the manned programs nor as obviously practical as, say, medical research. Newell found this regrettable, because he felt that the exploration of the solar system was potentially more comprehensible to the average citizen than some other sciences.[5] But an unmanned satellite, crammed with miniaturized electronics, silently transmitting measurements from orbit to other instruments on the ground, was not something to stir the imagination. From that standpoint, not even some of OSS's dramatic "firsts"—photographs of the earth from orbit or of the moon from its surface—could match the challenges of manned spaceflight: human challenges, easily understood, which naturally drew the lion's share of public attention.

The technological challenges of Apollo drew the lion's share of NASA's research and development funds, too. In FY 1960, before the first manned Mercury flight, OMSF got 45.5% of those funds to OSS's 34.6%; four years later the proportions were 69.7% and 17.6%. Scientists often complained about what they saw as a disastrous imbalance in

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* In Oct. 1967 Newell became associate administrator, NASA's third-ranking official. He retired in 1973.

NASA's priorities. It took years to convince some of them that Apollo was a national goal whose importance was not determined by its scientific value.[6]

Committed to a broad scientific program, OSS was much less single-minded than OMSF. By its very nature, scientific research is less goal-oriented than engineering. Programs in astronomy or space physics are intrinsically open-ended, although individual projects usually have limited objectives within a larger framework. Constrained by funds rather than time, scientists who worked with OSS were content with a more deliberate pace than the one that prevailed in OMSF. They also accepted a lower degree of reliability in their launch vehicles than manned spaceflight could afford, because in the long run that policy produced more scientific results for the money.[7]

Manned spaceflight was different. The problems defined by Apollo were mostly engineering problems, and OMSF was staffed largely by engineers, from George Mueller on down. Driven by the time deadline for accomplishing the manned lunar landing, they were interested only in answers to their specific and usually immediate questions. The manned programs drew on results from OSS's work—for information about the radiation environment in cislunar space, for example—but OMSF engineers were not interested in conducting that kind of research unless the information was not otherwise available.[8]

The one thing OMSF could not tolerate was operational failure. From the beginning, the survival of the astronaut and the completion of all mission objectives were the primary concerns. Elaborate test programs ensured that every part of a manned spacecraft or its booster met rigorous standards of safety and reliability. Every test, every inspection was thoroughly documented for possible analysis in case of failure. It was one thing if a Delta booster failed and an astronomy satellite was lost; it was something else again if a Titan exploded with two men in its Gemini spacecraft.

ORGANIZING FOR MANNED SPACE SCIENCE

America's first manned space program, Project Mercury, was an engineering and operational program that had no plans for science until late in the program. Little time or money could be spared for activity that did not contribute directly to the lunar landing. After the first orbital mission, when it appeared that scientists wanted to conduct some experiments in orbit, MSC Director Robert Gilruth formalized procedures to ensure that experiments were properly conceived and integrated into the mission. He established a Mercury Scientific Experiments Panel (later the MSC In-Flight Experiments Panel), made up of representatives of 11 MSC divisions and program offices plus an ex officio member from

OSS's Manned Space Sciences Division. The panel's job was to review and evaluate proposed experiments, taking into account scientific merit, relevance to manned spaceflight, impact on the spacecraft, and operational feasibility.[9] Though the directive establishing the experiments panel stated that "the Center encourages the development of worthwhile investigations," MSC acquired a reputation for being uninterested in scientific experiments, if not downright hostile toward them. Some scientists complained that the paperwork required to prove the experiments safe and reliable made them too expensive; some simply felt that engineers did not understand scientific investigation. For their part, engineers found the scientists somewhat casual about schedules, changes, and the impact of their experiments on operations. Still, the two groups found enough common ground to get a few simple visual and photographic observations performed on the Mercury flights.[10]

Those experiments were of small importance in themselves, but they showed that man could make useful observations from orbit. Determined to do better in Gemini, Homer Newell in 1963 established a Manned Space Sciences Division to work with the Space Sciences Steering Committee (the OSSA review board for experiments), scientific investigators, and MSC's experiment coordinators to bring together the scientific and engineering objectives of NASA. Its director reported both to Newell and to his OMSF counterpart, Brainerd Holmes. For the time being OMSF made no organizational changes for experiment management; it was left to the In-Flight Experiments Panel in Houston.[11]

Under the Headquarters administrative structure worked out after the Apollo decision in 1961, OSSA had responsibility for all the agency's science programs, but OMSF had full control of manned flights. Thus OMSF had the money for experiments in the manned program, but OSSA was supposed to oversee them. It was an awkward arrangement, but though Newell pointed out the difficulty to Associate Administrator Robert Seamans, Seamans would neither change it nor reallocate experiment funds to OSSA after Congress had approved the budget. In mid-1963 deputies for Newell and Holmes signed an agreement meant to define a workable relationship. OSSA was to solicit, evaluate, and select experiments for flight and develop experiment hardware to the "breadboard" stage.* OMSF then would select a center to develop the flight hardware, contract with experimenters and equipment developers, and carry the experiment through testing and development to flight. OSSA would also plan and develop the science training program for astronauts, but OMSF would conduct it. The arrangement was workable, if not ideal for either office, and early in 1965 Newell and George Mueller renewed it with only minor changes.[12]

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* A breadboard experiment is a working model containing all the components of the flight model but not permanently assembled. It is put together to prove that the experiment works and to allow easy modification during design studies.

In August 1963 Newell formally initiated the Gemini science program, sending out 600 letters to scientists describing the spacecraft and mission plans and soliciting proposals for experiments. A Panel on In-Flight Scientific Experiments then screened about 100 proposals, rejecting those having little scientific value or poor flight feasibility and passing the rest to the Manned Space Science Division of the Space Sciences Steering Committee. After the proposals were reviewed by appropriate disciplinary subcommittees within OSSA, the steering committee recommended 12 experiments to OMSF for flight on the Gemini missions.[13]

Meanwhile Brainerd Holmes was encountering complications with NASA's agreement to fly Air Force experiments on Gemini spacecraft whenever possible. The involvement of DoD made the program complicated and sensitive enough that Holmes sent several OMSF observers to participate in Houston's review of experiments; the In-Flight Experiments Panel would report its recommendations to Headquarters, and the joint NASA-Air Force Gemini Program Planning Board would assign experiments to flights. Holmes also prescribed priorities for Gemini experiments: first, NASA experiments directly supporting the objectives of Apollo (including medical experiments); second, DoD experiments; third, other experiments.[14] Since most scientists' experiments fell into the third category, they had reason to feel that they were being tolerated but not very strongly encouraged.

After taking over from Holmes in the fall of 1963, George Mueller decided to tidy up the experiments operation and at the same time get all the strings firmly in Headquarters' hands—an arrangement he much preferred. One of his first proposals was to set up a board under OMSF to coordinate all manned spaceflight experiments. After discussion with OSSA, where some objected that the proposed board's charter usurped too many of OSSA's prerogatives, Mueller issued a directive establishing a Manned Space Flight Experiments Board on 14 January 1964.[15] The new board, with an executive secretary and a full-time staff in Washington, would conduct the staff work necessary in coordinating the experiments. The directive established four categories of experiments (scientific, technological, medical, and DoD) and the channels through which they came to the board. Each sponsoring office solicited proposals, evaluated them, and forwarded them to the experiments board; the staff sent them to the appropriate OMSF program office (Gemini or Apollo) for a determination of flight feasibility; and the board approved or disapproved each experiment for flight. If it could not agree unanimously, Mueller made the final decision. The board gave each experiment a priority ranking within a master list; Mueller assigned each approved experiment to one of the centers for development.[16]

The Manned Space Flight Experiments Board effectively superseded MSC's In-Flight Experiments Panel, but Houston retained the important function of assessing feasibility. In March 1964 Gilruth consolidated his center's machinery for reviewing experiments under an Experiments Coordinating Office in the Engineering and Development Directorate. This office drew support from Flight Operations, Flight Crew Operations, the Gemini and Apollo program offices, and center medical programs, all of which were concerned with technical or operational feasibility. Each experiment was assigned an MSC technical monitor to work with the principal investigator and see the hardware through development.[17]

Thus by the time its second program started, OMSF had the organizational machinery to solicit, evaluate, and develop experiments. Scientists disliked the cumbersome bureaucratic system, especially the detailed documentation it required; but NASA had to make certain that experiments were scientifically worthwhile, that they would work in flight, that the crews knew how to operate them, and that they would not jeopardize a mission or an astronaut. On the whole the system worked; its main features were retained during the rest of the manned spaceflight program.

Experimenters learned their trade in the Gemini program, where scientific research became a part of manned spaceflight. On the 10 Gemini flights 111 experiments were performed: 17 scientific, 12 technological, 8 medical, and 15 DoD;* 36 investigators from 24 organizations participated. The official assessment of results was, "The experience gained from the Gemini Experiments Program has provided invaluable knowledge and experience for future manned space-flight programs." Unofficially, many of those involved agreed that the results were comparatively unimportant as science; the chief value of the experiments was in working the kinks out of the experiment-management routine.[18]

Getting experiments on board the spacecraft was not as straightforward as the system implied. Scientists, astronauts, flight planners, and spacecraft engineers all had to learn as they went. Time, and some failures, taught them how to design experiment hardware, assure its reliability and flightworthiness, engineer it into the spacecraft, integrate it into the timeline, and train the crews to operate it. Much of the traditional scientist-engineer antipathy can be read into the stories told by participants. Scientists chafed under the inflexible requirements of the engineers, who found scientists blithely unconcerned about such details as schedules and last-minute changes. The cooperation displayed by astronauts varied, to say the least; some took the experiments seriously, but others considered them a nuisance (and said so). When it was over, scientists and spacemen understood each other better and, for the most part, professed satisfaction with the results.[19]

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* Many of the experiments were repeated on several flights.

Gemini gave medical investigators their first chance to answer some crucial questions that had been raised by the Mercury flights, during which the medics' principal task had been to support flight operations. While Mercury had allayed many of the fears expressed in the 1950s, it had also produced evidence that weightlessness had potentially serious effects on the circulatory and skeletal systems. Gemini's longer flights offered the chance to monitor physiology more extensively and to conduct some inflight medical experiments.[20] As in Mercury, managers in Gemini were primarily interested in medical certification that weightless flight was safe—at least for eight days, the anticipated length of a lunar landing mission. Medical researchers, however, aware of the marked individual differences among crewmen, wanted as much data as they could get, to give their conclusions a better statistical base. After the eight-day flight of *Gemini 5* in August 1965, pressures mounted to discontinue the medical studies, which cut deeply into training and flight time.* *Gemini 7* (4–18 Dec. 1965) was the last flight to conduct more than one medical experiment.

The Gemini missions dispelled the major concerns about weightlessness on short flights, but also indicated some trends that could become serious on long-duration flights. The questions left unanswered at the end of Gemini provided the rationale for the medical program on AAP: How does the body adapt to weightlessness? How long do the changes continue? What countermeasures might be effective?[21]

SCIENTISTS AND MAN IN SPACE

The early scientific satellites were small, built to be launched on available boosters, and relatively inexpensive. They were also remarkably successful. Scientists who flew payloads in the early days accepted the limitations, since they were offset by comparatively low cost, which made more flights possible. President Eisenhower's science advisers saw no compelling reason to hurry into manned spaceflight. From the scientific point of view, manned flight was far too expensive for the results it might return, which seemed to be almost nil. The Soviets' apparent attempts to acquire prestige by launching the first man into space did not disturb this view. The President's Science Advisory Committee (PSAC) belittled the significance of man in space, advised against being drawn into a race with the Russians, and steadfastly backed the space science program as the more valuable phase of space exploration. That was also the phase in which the United States was leading and could maintain its lead.[22]

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* Pre- and postflight medical measurements were not so troublesome, but inflight experiments were something else. One experiment (M-5, Bioassay of Body Fluids) required collecting and returning urine samples; even worse was M-7, Mineral Balance, which required strict control of diet and collection of *all* feces and urine before, during, and after flight. It was done only once, on *Gemini 7*. For one astronaut's comments on the Gemini medical experiments, see Michael Collins, *Carrying the Fire: An Astronaut's Journeys* (New York: Farrar, Strauss, and Giroux, 1974), pp. 145–48.

John Kennedy understood the wider appeal of manned spaceflight and determined to put the U.S. ahead in all phases of space exploration; but his science adviser, Jerome Wiesner (a member of PSAC from its inception in the Eisenhower days), tried to change the new president's mind. A task force headed by Wiesner reported on 12 January 1961 that the emphasis on Project Mercury was wrong; instead, NASA should play down Mercury's importance and find ways "to make people appreciate the cultural, public service, and military importance of space activities other than space travel."[23] Beset with problems, Mercury offered the U.S. little chance of surpassing the Soviets at an early date.

NASA, however, had its own outside consultants to provide scientific advice—the Space Science Board of the National Academy of Sciences,* created in 1958. The Space Science Board took a different view of long-range policy for the space agency. A month after Wiesner's report, the board urged that plans for early expeditions to the moon and the planets be based on the premise that man would go along. "From a scientific standpoint," the board said, "there seems little room for doubt that man's participation . . . will be essential, if and when it becomes technologically feasible to include him." The board saw little difference in the scale of effort needed to send man on space explorations and that necessary to approach his capabilities with instruments. There was no mechanical substitute for trained human judgment.[24]

Kennedy's decision to commit the nation to Apollo established the dominance of technology over science in NASA's programs. Scientists immediately objected to the space program becoming, as one astronomer told Sen. Paul Douglas of Illinois, "an engineering binge instead of a scientific project." Space scientists, justifiably proud of the sophisticated instruments they had developed, were disappointed that the public did not appreciate the scientific leadership they represented.[25] Many scientists took the Wiesner-PSAC view to the public in the period following the Apollo decision, but they were fighting a losing battle. Acceptance of "man on the moon in this decade"—and Congress emphatically had accepted it—dictated an engineering program to develop launch vehicles and spacecraft that dominated NASA's budget and the public's attention until it was completed. Scientists who opposed it underestimated the fascination that this gargantuan technology held for the media and the public.

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* The Academy is a private, unofficial body chartered by Congress in 1863; its purposes are to advance the cause of science generally and to advise the government on scientific matters when requested. Membership is a mark of eminence in research second only (perhaps) to the Nobel Prize, though many first-rank scientists are not members. Daniel S. Greenberg, "The National Academy of Sciences: Profile of an Institution," *Science* 156 (1957): 222-29, 360-64, and 488-93; idem, *The Politics of Pure Science* (New York: The New American Library, Inc., 1967), pp. 12-15.

The Space Science Board's attitude was different. Accepting the Apollo goal, the board worked for the best scientific program that could be achieved within the Apollo framework.[*] It had endorsed manned lunar and planetary exploration in 1961; and the next year, in its first summer study undertaken at NASA's request, it reaffirmed that endorsement. Ninety-two academic and industrial scientists participated in the 1962 summer study, which was principally concerned with the state of the unmanned program and NASA's plans for its future. But there was a working group on "Man as a Scientist in Space," and the role of man received more attention than might have been expected. The report noted that man's judgment and ability to evaluate a total situation far exceeded anything machines could do, and concluded that a scientifically trained man was essential to adequate exploration of the moon and the planets. The working group recommended that Ph.D. scientists be recruited for training as astronauts as soon as possible, preferably in time to be included in the first crew to land on the moon.[†] Meanwhile astronauts already in the program should be given as much scientific training as possible.[26]

The working group's conclusions took into account the replies to a questionnaire the Space Science Board had sent to space scientists a few months before, seeking their opinions on the role of scientists in Apollo. The responses reflected the view that each flight should include at least one crewman who was a scientist first and an astronaut second. The man who landed on the moon should be an expert who could collect samples quickly but with great discrimination. Scientist-astronauts should be allowed to continue their professional scientific development; hence the respondents hoped that astronaut training "would not involve too large a fraction of their time," perhaps only a part of each year. (This seemingly cavalier attitude toward the skills required of astronauts may have been only naive, but it was matched by the astronaut office's view of scientists. That view, pithily summarized by a NASA official a few years later, was that "it is easier to teach an astronaut to pick up rocks than to teach geologists to land on the moon." Reconciling these views took time.)[27]

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[*] According to one knowledgeable science journalist, the SSB could do little else. Concerning the board's role in advising NASA, Daniel Greenberg wrote, "Early in the relationship NASA made it clear . . . that it was not the least bit interested in the Board's view on whether there should be a manned space program. . . . For a variety of reasons . . . there was to be a large-scale space program, and if the Board wished to provide advice on its scientific components, NASA would be pleased to consider it." *Science* 156 (1957): 492.

[†] The first scientist-astronauts were recruited in 1965, the second group in 1967. Of 17 scientists recruited, plus one who qualified as a pilot, only one (a geologist) went to the moon, on the last mission. Three others flew in Skylab. *Astronauts and Cosmonauts, Biographical and Statistical Data*, report prepared for the House Committee on Science and Technology, June 1975.

The summer study did not look beyond Apollo, giving only brief consideration to earth-orbiting laboratories. The report commented only that "the time phasing and form of such a laboratory needs further study." The primary role for an orbiting laboratory seemed to be in biological studies, although it would likely be useful as a base for modification, maintenance, and repair of orbiting satellites. Astronomers believed that telescopes should not be mounted in manned orbiting stations, since the motion of the occupants would disturb the alignment of the instruments.[28]

Although the report accepted the necessity for science to take second place in Apollo for the time being, it contained clear evidence that some scientists were unhappy with the lunar landing program and had not been reluctant to say so. Noting that considerable confusion existed about the Apollo mission and its proper justification, the report's authors urged NASA to justify Apollo's cost in terms of the scientific capability it would provide after the technological goal had been achieved. At the same time they called on scientists to recognize that the Apollo goal grew out of many considerations, most of them nonscientific, and to accept that as something they—and NASA—had to live with.[29]

Within a year scientists who had feared Apollo's fiscal appetite found their apprehensions well grounded. Preliminary consideration of NASA's FY 1964 budget in the fall of 1962 almost led to the sacrifice of unmanned science programs. Only a convincing argument from Administrator James Webb persuaded the president to leave them alone.[30] When NASA went to Congress in the spring of 1963 asking for $5.71 billion, talk of budget cuts became common. Webb and his lieutenants held out, however, insisting that the 1970 goal could not be met on a smaller budget. Whether from a belated realization of the magnitude of the Apollo commitment—at least $20 billion—or because of the sudden sharp increase in NASA's budget request, critics raised questions about the nation's priorities, calling the lunar program a technological stunt that would cost far more than it was worth. During the spring and summer a number of respected scientists (most of them not connected with the space program) added their voices to the chorus of objections.

Philip H. Abelson, editor of *Science* (the weekly journal of the American Association for the Advancement of Science), touched off the scientists' protests with an editorial on 19 April 1963. Examining the justifications that had been advanced for Apollo, Abelson found them inadequate. Its propaganda value was overrated. The prospect of military advantage was remote. "Technological fallout" could never recover more than a fraction of the project's cost. As for scientific return, Abelson saw practically none, especially since no scientist was likely to be in the first crew to reach the moon. Unmanned probes, each costing perhaps 1% of the price of an Apollo mission, could return more and better data. Furthermore, they could provide information needed in the design of a manned landing vehicle.[*] In sum, he could find no justification for the high priority given to Apollo.[31]

Abelson opened the door for a crowd of critics. For the next month or so, "Scientist Blasts Moon Project" could have been used as the headline for many a news story. Nobel Prize winners volunteered their condemnation. Defenders of Apollo replied, and a full-dress debate was on. NASA Deputy Administrator Hugh L. Dryden accused Abelson and others of setting up a straw man to knock down: "No one in NASA," he said, "had ever said the program was decided upon solely on the basis of scientific return." An aerospace magazine offered the opinion that the critics ("an esoteric wing of the scientific community") were unhappy because engineers were successfully pursuing goals that scientists considered unseemly. Eight noted scientists (three Nobel laureates among them) acknowledged Dryden's point and called Apollo "an important contribution to the future welfare and security of the United States."[32]

The brouhaha swirling around Apollo and its scientific importance could not escape congressional notice. In June, before resuming deliberations on NASA's budget, the Senate Aeronautical and Space Sciences Committee scheduled two days of hearings on the subject and invited 10 prominent scientists to testify. Senators heard little they could not have read in their newspapers; scientists had the same reservations about Apollo as other concerned citizens (plus one or two of their own) and had the same axes to grind as other lobbyists.[†] They argued that many goals were more worthy of $20 billion than a moon landing: aid to education, social programs, medical research, the environment, improving the cities—even support for other areas of science. Harry H. Hess, chairman of the Space Science Board, and Lloyd V. Berkner, its first chairman, presented the familiar NASA point of view. On one point, at least, the witnesses generally agreed: in some situations the presence of a scientifically trained observer would be worth the cost of getting him there.[33]

Criticism from the scientific community died down somewhat as the summer ended. Abelson continued to snipe at Apollo from time to time, but by early 1965 he was ready to give up his campaign. If people wanted the moon explored, he told an interviewer, it was all right with him, provided "the public realizes it is chiefly for fun and adventure and not because some great contribution is being made to science." The heart had gone out of the scientific opposition, and as Daniel Greenberg wrote, "with Lyndon Johnson wholeheartedly for going to the moon and with most of the capital investment for that project already paid for, it is going to take more than a few dissents to inspire Congress to toy with Apollo."[34]

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[*] This, of course, was done. Surveyor, Ranger, and Lunar Orbiter missions assured the feasibility of landing, provided useful data for the design of the lunar landing module, and certified the sites chosen for Apollo landings.

[†] Lee DuBridge, an experienced scientific adviser to government, bluntly made one point that others usually mentioned more delicately. If NASA's budget were cut, he said, the agency might shift funds from its Sustaining University Program to Apollo—something that DuBridge, president of Caltech, felt would be a great mistake.

The effect of this opposition on plans for the first lunar landing was nil. Its effect on NASA policies became apparent only later. When it appeared that Apollo would succeed, lunar scientists (who wanted to make sure the right things were done on the moon) and MSC engineers (who began to see scientific exploration as the best justification for additional lunar landings) saw that they needed each other and worked toward accommodation. From *Apollo 12* on, relations between lunar scientists and the Houston center consistently improved.[35]

Events of 1964 indicated that the Space Science Board had been listening attentively to the debate of 1963. When President Johnson asked James Webb for a new look at space goals, NASA asked the board to reexamine its 1961 statement and consider what should follow Apollo. The board had always supported NASA on the question of man in space—its 1961 statement, in fact, had been ahead of the agency on the question of manned space science—but now it backed away from strong endorsement of manned projects. In its report of 30 October 1964 setting forth national goals in space for 1971–1985, the board affirmed the basic goal of exploring the moon and the planets, but relegated manned exploration to second place. It named Mars as the target for intensive unmanned exploration; while that was under way, the solution of biomedical problems should be pursued "at a measured pace, so that we shall be ready for manned [Mars] exploration by 1985." OSSA's space science program should be continued, and in some areas expanded. The board urged a balanced and flexible scientific research effort, able to respond to unexpected opportunities. Money should be spent where the probability of scientific return seemed greatest. Such a program, using Apollo-developed hardware and operational capability, would ensure a steady flow of scientific dividends from space even if Apollo met with unforeseen delays. Lunar exploration and manned orbital stations warranted "significant programs, but are not regarded as primary because they have far less scientific importance." An earth-orbiting station was more important for developing operational techniques than for scientific work.[36]

Late in 1964 NASA asked the Space Science Board to convene another summer study, this time to consider post-Apollo programs in space research—specifically planetary exploration, astronomy, and manned space science. Participants met at Woods Hole, Massachusetts, in June and July 1965 to formulate their recommendations. The summer study report generally agreed with the Space Science Board's policy statement of the previous October, but found more justification for man's participation in space research. Most of the report consisted of suggestions for improving OSSA's unmanned science programs. It endorsed the exploration of Mars as the principal goal for the immediate future. As to policy, NASA should aim for a balanced program. The distinction between manned and unmanned space science was artificial; for any given investigation the mode should be chosen to give the best scientific results. Again the scientists emphasized the need to train more scientist-astronauts, suggesting that scientific knowledge would become more important than piloting skills as the manned program matured. Of particular interest to AAP planners was an endorsement of a solar telescope mount for the Apollo service module (see below) and the strong recommendation that an earth-orbiting laboratory was needed to study man's response to the space environment.[37]

George Mueller and Homer Newell made what they could of the advice of the Woods Hole study when they testified before congressional committees in the spring of 1966. Mueller saw the orbital workshop as an important step toward the long-term space station—a low-cost way to gain experience before flying a six- to eight-man laboratory. Newell was gratified that the proposal for a telescope on the Apollo spacecraft found favor, but otherwise the report called for a more ambitious program than OSSA would be able to support. In fact, budget cuts had already forced OSSA to cancel the Advanced Orbiting Solar Observatory (AOSO), a project the summer study had enthusiastically endorsed.[38]

SOLAR OBSERVATORIES IN ORBIT

The loss of AOSO was keenly felt, because study of the sun was one of OSSA's major activities. Already two Orbiting Solar Observatories (OSOs) had been launched, with gratifying results. The OSOs collected data on solar radiation, especially those wavelengths (ultraviolet and x-ray) that do not penetrate the atmosphere. AOSO was to have been much bigger, with better stabilization and pointing accuracy, higher resolution, the ability to detect and respond to transient events such as solar flares, and 10 times as much data-storage capacity. The $167.4-million project had called for four AOSOs to be launched through 1971, providing coverage of the period of maximum solar activity* expected in 1969. By July 1965 conceptual design studies had been completed and the contract for the prototype was being negotiated.[39]

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* The sun's overall activity, measured in terms of radiation and magnetic effects, varies in a period averaging 11 years from one maximum to the next.

Severe cuts were made in NASA's budget requests during 1965, however. OSSA was reduced by 16%, from $783.2 million in FY 1966 to $661.4 million in its FY 1967 request. Hard choices had to be made. Many projects were cut back, but AOSO had to be canceled, because its funding requirements were particularly high in the upcoming fiscal year.[40] The OSOs would continue, and although they might take on some of the work that AOSO would have done, they could provide neither the quality nor the quantity of data that the second-generation observatory was designed to gather.

Homer Newell was worried as 1966 began, not so much for the loss of AOSO as for the survival of a significant space-science program. He could hardly help remembering the close call that space science had had only four years before, and he saw the same pressures building again. Early in the new year he sought help from Gordon MacDonald of UCLA, who had served on both the President's Science Advisory Committee and the Space Science Board and was an active supporter of OSSA's programs. Newell wrote him that the accomplishments of space science once again were in danger of being overshadowed by the glamour of manned spaceflight. With the nation committed to Apollo and money getting harder to come by—Vietnam was starting to make substantial demands on the nation's resources—space science would suffer. If scientists did not demand support for a first-class research effort, Congress would not give it. Budget cuts already made with little protest from scientists were fostering an attitude that the programs were less important than OSSA had said. Manned space science needed outside support too. The volume and weight capabilities being developed in Apollo were enormous, and academic scientists had not come close to making full use of them. Without high-quality proposals from outside, "there is a strong tendency [in OMSF] to get experiments just to have experiments to fly." Newell's staff was trying hard to keep the manned program scientifically respectable, but help was needed. He urged MacDonald to speak out, to testify before congressional committees if he could, and to "prod and needle some of your colleagues to do the same."[41] Newell was having to rally space scientists to their own cause; the vigorous protests of 1963 were not heard in 1966.

Meanwhile, OSSA was doing what it could. In September 1965 the Physics and Astronomy Section had moved to establish a foothold for astronomy in manned spaceflight. A six-month contract to study the feasibility of installing a telescope mount in the Apollo service module was awarded to Ball Brothers Research Corporation of Boulder, Colorado, a long-time designer and builder of instruments for OSSA programs. The study was to determine whether astronomical instruments on a manned spacecraft could be stabilized enough to gather good data and whether man would be useful in making observations from orbit. Called at first the Apollo telescope orientation mount, the device soon became known simply as the Apollo telescope mount or ATM.[42]

The key features of the ATM were provision for control and adjustment by the astronauts and use of photographic film to record data.* It could not replace AOSO, because AOSO had been designed to observe the sun continuously for 9 months while the proposed ATM flights were limited to 14 days. But after AOSO was canceled, the ATM became the only possibility for observing the solar maximum with high-resolution instruments. OSSA thus had an important scientific project in need of a vehicle at the same time OMSF was looking for important scientific experiments to fly in the Apollo Applications Program. Newell and Mueller began talking about combining the two early in 1966.

As the program offices discussed ATM, a number of points had to be settled. Management was one. Goddard Space Flight Center was experienced in astronomy programs and had directed the Ball Brothers study, but the OMSF centers were more experienced in integration on manned vehicles. Toward the end of January Newell's office asked Langley, Marshall, Goddard, and MSC to submit proposals for managing the ATM project. Three proposals were received—Langley could not spare the resources to support the project—and after reviewing them OSSA decided to leave the project at Goddard. With that question settled, Newell asked Deputy Administrator Robert Seamans for approval of the project, citing the need to get started immediately: only two and a half years remained before the 1969 solar maximum. The project approval document Newell submitted noted that the instruments were compatible with several locations in the spacecraft, but specifically mentioned the service module's experiments sector as the current concept.[43]

Mueller, however, was committed to using the lunar module as an experiment carrier, and he wanted the ATM mounted there. At an AAP status review on 8 April 1966, Newell, Mueller, and their technical experts reviewed both proposals for Seamans. OSSA argued that mounting the ATM in the service module was cheaper and more certain of success; it required fewer changes to the spacecraft; and it could meet the scientifically important 1968 launch date. Against that only a single 14-day mission was possible, because the service module burned up on reentry. OMSF asserted that the lunar module-ATM combination would require less money immediately; it could be left in orbit and reused; and subsequent use of the lunar module as a laboratory would be facilitated by the experience gained with the ATM. On the other hand the lunar craft was totally untried and its production was lagging. Neither option seemed clearly preferable, and Seamans asked for more details. He

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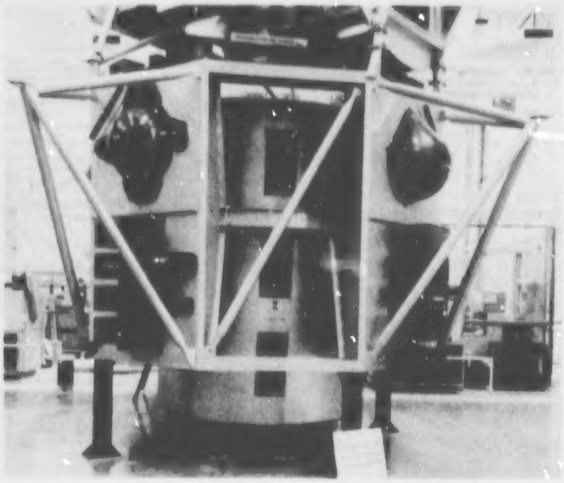
* Film was not normally used in unmanned satellites because of the difficulty of recovering it from orbit. For some purposes, however, astronomers preferred film to electronic detectors because of its superior resolving power. On a manned mission film could be brought back by the crew.



A mockup of the Apollo telescope mount installed in the lunar excursion module, January 1967. The combination was never built. MSFC A49627.

was reluctant to approve the project immediately, because he could see no way to fund the ATM's FY 1967 requirements and thought it unwise to start a competition in industry until the agency could follow up with immediate development. Meanwhile he approved two more studies by Ball Brothers, one to study automatic operation of the ATM if it could be left in orbit after a manned mission, the other for studying adaptation of the ATM to the lunar module.[44]

Mueller saw a Marshall-based ATM project as the solution to several problems, but he was already getting objections from within his own organization. A strongly worded letter from Robert Gilruth (pp. 45–46) was on his desk while the project was being discussed with Seamans; the MSC director objected both to the use of the lunar spacecraft as a laboratory and the assignment of integration to Huntsville. Ignoring Houston's protest, Mueller went ahead. He decided on 18 May that the entire ATM system, except for the telescopes themselves, would be designed, built, and integrated into the lunar module at Marshall. On 8 June Huntsville planners started talks with the lunar module's prime contractor, Grumman Aircraft Engineering Corporation, and shortly thereafter MSC authorized Grumman to study the compatibility of the ATM with the lunar module. OSSA objected to a mission assignments document issued in June by the AAP office, because the orbital altitude and inclination, proposed launch dates, and operational plans did not agree with OSSA's intentions.[45] Again, Mueller pressed on.

Newell and Mueller met with Seamans several times in June and July, seeking his signature on their competing project approval documents. On 11 July the three agreed that the entire ATM project, experiments and all, should be transferred to Marshall for development. This decision resulted from a growing feeling at Headquarters that it was best not to divide responsibility for such a complex project, and Goddard could not manage the whole package alone.[46] After that, it was a safe bet that Mueller's plan would be adopted. He continued to give Seamans technical data, including the results of tradeoff studies comparing various locations for the ATM and recommending that it be mounted on the lunar module.

In Houston during the *Gemini 10* mission (18–20 July 1966), Mueller asked MSC officials to comment on those studies. In response, the Houston staff agreed that all the ATM work should be assigned to Marshall, but maintained that selection of the lunar module as the experiment carrier would forfeit all the benefits gained by that assignment. Instead, Marshall should design and build a special structure to carry the ATM and its supporting systems—a "rack" that could be launched inside the CSM-LM adapter. In orbit the crew would operate the solar telescopes from the command module. Up to 30 days of observation could be conducted if the mission used an Extended Apollo spacecraft. MSC calculated that modifying the lunar module as Mueller proposed would cost at least $100 million more than a rack and might take two or three years longer.[47]

MSC's managers also objected to Mueller's proposed plan for operations, which required the Apollo spacecraft to rendezvous with the separately launched telescope mount. Two crewmen would move into the solar observatory, which then separated from the CSM. After conducting 14 days of solar observations, the ATM vehicle rejoined the Apollo craft and the two crewmen returned to the command module. If the second rendezvous could not be accomplished, however, the ATM crew had no way to get home. This risk MSC absolutely could not justify for such a mission. On safety considerations alone, Houston "could not support the proposed Apollo Applications LM/ATM approach." [48]

Other factors contributed to MSC's opposition to Mueller's plan. The summer of 1966 was a particularly trying time for the lunar-module project. Grumman was experiencing severe technical and management problems, and the MSC program office had its hands full trying to find a way out of two years of serious difficulties. They did find a way, in spite of Mueller's insistence on complicating their problems by bringing in another project and another center. Eventually MSC's Apollo Spacecraft Program Manager asked Mueller directly why he continued to back the lunar-module laboratory in the face of all its technical drawbacks; were not his motives at least partly political? Mueller's reply was that they "were not partly political but completely political."[49] The necessity to hold the Marshall team together, combined with the need to avoid anything that looked like a major new project, left him little maneuvering room.

Houston's objections could not be completely ignored at Headquarters, however, and on 2 August OMSF recommended that Seamans approve a derivative of the MSC suggestion. Reexamination of funding requirements and manpower resources at Marshall now indicated that the optimum procedure was to contract for some $60-million worth of major components of the LM-ATM system and to use Marshall personnel for selected development tasks. Mueller said that the 1968 launch date could be met, given immediate approval and initiation of work. Opinion in OSSA was not too hopeful of launching the ATM in time to observe the sun during its period of maximum activity, but that office nevertheless seconded Mueller's call for immediate approval.[50]

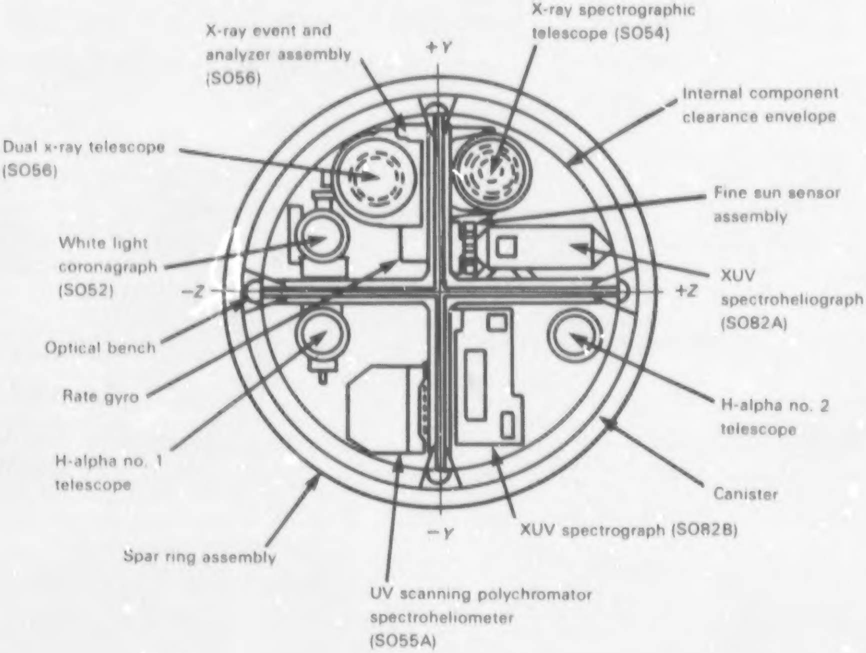
On 29 August 1966, five days after the Senate completed congressional action on NASA's FY 1967 appropriation, Seamans signed Mueller's version of the ATM project approval document, authorizing development of one set of instruments for flight on the second Apollo Applications mission. Noting that several important details were undefined, Seamans asked to be kept informed of major decisions made during the project definition phase. The next three months were spent in working out the ATM design and operating mode, culminating in the orbital cluster based on the multiple docking adapter (pp. 36–39). Experimenters, who had been waiting four months to go ahead with building their instruments, were now free to do so. Design of the AOSO instruments had not gone very far when that project was terminated, and OSSA had kept them alive, hoping to find a way to use them. The Goddard ATM team had kept interest alive by organizing a betting pool on the date Seamans would sign the project approval document. The development schedule to get the instruments on the ATM was now very tight, but neither Goddard nor the experimenters could help that.[51]

Although the waiting was bad for the experiments schedule, it provided time to settle some basic questions about the mount. Besides the issues discussed already, there was the problem of stabilizing the ATM to the degree required. The main purpose of the project was to get the superior resolution that film could provide, and for this it was essential that the mount be extremely stable. Specifications called for holding the telescopes' alignment within ±2.5 seconds of arc for 15 minutes at a time—equivalent to keeping the ATM pointed at the bridge of a man's nose, a kilometer away, without allowing it to drift as far as the pupil of either eye. Some experimenters did not believe this could be accomplished. Conventional attitude-control thrusters could not handle such requirements, so at the May AAP review Mueller decided to use gyroscopes as the basic means of stabilizing the ATM. Research at Langley had produced prototypes of "control moment gyros" with 90-centimeter rotors, large enough to stabilize a vehicle the size of the ATM. More work would be required to qualify these for long-term reliability in space, and both Langley and Marshall set about it.[52]

Three days after Seamans approved the project, four agencies were notified that their experiments had been selected for ATM. On 6 September the contracts were transferred from Goddard to Marshall; on the 19th the basic ATM program was approved by the Manned Space Flight Experiments Board. Marshall's compatibility studies for the LM-ATM hardware and mission, presented at the board meeting, showed an experiments canister 1.5 meters in diameter and 3.3 meters long, carrying the instruments on a cruciform spar that divided the canister into quadrants. The canister could be mounted on a rack attached to the ascent stage of the lunar module. The estimated weight was within the capability of the Saturn IB with a comfortable margin.[53]

The five instruments, capable of recording the sun's spectrum from visible light to high-energy x-rays, constituted a coordinated approach to solar research never before attempted. Few laymen would recognize any of the instruments as a telescope, although all but one could record images of the sun (or small regions of it) on film. The Naval Research Laboratory's two ultraviolet instruments could photograph the entire sun or selected small areas, using wavelengths that revealed the composition of the area under study. American Science and Engineering of Cambridge,

Cross section through the telescope mount canister, showing the cruciform spar and instruments.


X-ray event and analyzer assembly (SO56)
+Y
X-ray spectrographic telescope (SO54)
Internal component clearance envelope
Dual x-ray telescope (SO56)
Fine sun sensor assembly
White light coronagraph (SO52)
−Z
+Z
XUV spectroheliograph (SO82A)
Optical bench
Rate gyro
H-alpha no. 2 telescope
H-alpha no. 1 telescope
Canister
−Y
XUV spectrograph (SO82B)
Spar ring assembly
UV scanning polychromator spectroheliometer (SO55A)

Massachusetts, was building an x-ray instrument to record detailed images of solar flares and to monitor the sun's x-ray output. The High Altitude Observatory at Boulder designed a white-light coronagraph, which, by blocking the intense light from the sun's disk, could photograph the much fainter corona. The only non-photographic instrument was Harvard College Observatory's ultraviolet spectrometer and spectroheliometer. It complemented NRL's instruments, but used photoelectric detectors and telemetered the readings to the ground. Thus it was the only instrument that could be operated remotely while the ATM was unmanned, although in that mode it lacked fine-pointing control, which was a function of the crew.[54]

Marshall's compatibility study turned up nothing to prevent scheduling the ATM for launch in the fourth quarter of 1968. There were some doubts that two of the instruments could be delivered six months before launch as required, but it was "intended that schedule incompatibilities be overcome during contract negotiations." The question of power for the module was still moot; planners spoke of an array of solar cells to generate up to three kilowatts of electricity. With the approval of the ATM instruments, AAP's largest and most complex scientific project was ready to get under way. Marshall's AAP office, as manager Lee Belew said, then "turned on a systems design effort that was for real."[55]

EXPERIMENTS FOR THE WORKSHOP

ATM deserved all the attention it got, but the workshop needed more than a set of solar telescopes to justify it. After so much talk of the importance of man in orbital science, it nevertheless turned out to be hard to find experiments that required man's participation and effectively used the workshop's large volume. The problem was graphically stated by Wernher von Braun in May 1965, when he noted that the optimistic schedule being proposed by Mueller would, if implemented, make it possible to put 970 metric tons of payload into a 225-kilometer orbit every year. A single Saturn V could orbit *all* of NASA's previous payloads at one time—and then some.[56]

Early in 1966 Mueller told the centers that funds for the experiment program would be short. They could not use contractors to develop experiments as they had done in the past, but would have to do it themselves. He suggested using off-the-shelf, commercially available components wherever possible. Von Braun passed the word along at Marshall, reminding his staff that their concern extended beyond the workshop: it would have to be filled with experiments. Huntsville and Houston then began preparing lists of things they would like to see done in the workshop.[57]

After the February 1966 AAP review, Robert Seamans directed

OMSF to include the experiments in these periodic examinations of the program's status. By March, 3 experiments were actually under development, 10 were being considered by the Manned Space Flight Experiments Board, and another 13 were ready to be submitted to the board. Eleven were in the definition phase, 108 were being planned for definition studies, and 72 were waiting for the process to begin. Since an experiment typically required 32 months from inception to flight readiness, the outlook for a substantial program of experiments for a 1968 workshop was not good. Money was the major problem, aggravated by inadequate manpower at the centers and the division of responsibility between OSSA and OMSF. Seventeen biomedical experiments had been identified, but work statements defining center responsibilities for them had not yet been written. The ATM, to which OSSA was giving top priority, was a promising project; but it needed $19 million, for which no source had been identified.[58]

Within OMSF the responsibility for early phases of experiments lay with E. Z. Gray's Advanced Manned Missions Office, and Mueller now urged that office into action. Gray responded by naming Douglas Lord chief of the Experiments Division and charging him with assembling a coherent set of experiments for the workshop. After preliminary discussions with experiments offices at Houston and Huntsville, Lord called on the centers in mid-May to submit a list of experiments they could make ready, along with priorities, development funding plans, and schedules, to present to the experiments board at its July meeting. A month later nothing had been received. When proposals did come in, Gray was not happy with them, and he minced no words in a message to von Braun and Gilruth on 28 June: "It is evident that the proposed workshop experiments do not constitute a reasonable program." For example, no experiments had been proposed to assess the habitability of the spent stage and provide design parameters for space stations. Several of the experiments did not really require the workshop; others needed little or no participation by the crew. "In my estimation," he concluded, "we have not faced up to the problem of defining a useful set of experiments which can be developed in our in-house laboratories and subsequently conducted in the workshop."[59]

Lord then took a team to the centers, "beating the bushes . . . to find low-cost experiments." "We hadn't put a lot of money into defining experiments," Lord recalled later, "so you really had to go out and try to find them, and there were not a lot." Von Braun said that "the complex system for getting experiments approved was so terrible it didn't matter how many we could find because we couldn't get them through the system anyway," at least not in time for a late 1968 flight. Still, Lord and his crew spent six months pressing the centers to devise experiments and getting them evaluated.[60]

Experiment reviews were held at Houston and Huntsville in August 1966. Twenty-four experiments, mostly engineering exercises, were scrutinized; 8 were rejected, 13 accepted, and 3 withdrawn or combined with others. Top priority was given to a "Habitability/Crew Quarters" experiment, with both centers participating. Other experiments aimed at determining how effectively astronauts could repair and maintain equipment, investigating the flammability of materials in zero gravity, and evaluating spacesuits and extravehicular mobility aids. Eleven of these were approved at the September experiments board meeting, on condition that funds for their development could be found. The board reminded both centers to keep costs down by using in-house facilities and manpower as much as possible.[61]

Rather surprisingly, considering that they had always been a prime justification for workshop-type missions, the medical experiments were slow to get started. Other activities were taking up all the available manpower at Houston, where that work was centered. The medical results of Gemini were still under evaluation and 16 medical experiments were being developed for earth-orbiting Apollo missions. Planning the Apollo experiments, evaluating the Gemini data, and conducting ground-based supporting research taxed the understaffed Medical Research and Operations Directorate at MSC. Similarly Houston's Crew Systems Division, which would have an important role in the development of medical experiments, was working at capacity on life-support and environmental-control systems, among other things.[62]

The most important medical studies for the first 28-day mission could nonetheless be defined, and at the September meeting of the experiments board OMSF's Office of Space Medicine presented three proposals. Two—Metabolic Activities and Cardiovascular Assessment—would measure the response of the muscular and circulatory systems to zero gravity, providing inflight data by telemetry. The third, Bone and Muscle Changes, was a continuation of the Gemini M-7 experiment (n., p. 63), requiring pre- and postflight measurement of calcium in bones and collection of urine samples in flight for later analysis. The board approved the medical experiments with the understanding that detailed plans would be provided later. It also concurred in a recommendation that a physician-astronaut be included in the crew of the first workshop mission.[*][63]

The next board meeting, in November, was a busy one, mostly occupied with AAP experiments. Two medical, four technological, and six scientific experiments were approved, subject to the usual condition that funding be found. By now the first workshop mission was beginning to be a bit crowded; the crew would not have enough time to carry out all the approved experiments. Another problem was posed by a proposed artificial gravity experiment; maneuvering fuel was insufficient to spin the cluster while maintaining a reserve to bring the command module out of orbit, should that be required. These two items pointed up the difficulty of integrating a group of diverse experiments with the operational requirements of the mission. A group at Marshall responsible for experiment integration was finding it a headache—especially since the experiments were changing every two months and the spacecraft was still being defined.[64]

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[*] Only one was then in the astronaut corps, Lt. Comdr. Joseph P. Kerwin, USN, later scientist-pilot on the first Skylab mission.

At that same meeting the board moved to deal with the related problem of experiment priorities. Sponsoring agencies established priorities for their experiments, but it was up to the board to work out an integrated list. First priority in November went to habitability, followed by the biomedical studies and crew mobility and work capability experiments. An artificial gravity experiment was in last place. These priorities were not binding and would be adjusted as the roster of experiments grew. The board would continue to wrestle with the priority problem for another full year.[65]

At the end of 1966, only 2 experiments were definitely assigned to specific missions. Thirty-one, including the ATM and the medical group, were approved and tentatively assigned; 19 were approved and awaiting assignment to a flight. With the adoption of the cluster concept and the definition of the first four launches (two missions)—a process completed only in December—the experiment program solidified considerably. By February 1967, all of the tentative assignments had been made definite, 8 more experiments had been scheduled, and several new ones had been proposed and approved.[66]

By the time George Mueller presented AAP to the press on 26 January 1967, the program was, as he indicated, making a substantial start in manned orbital science. The medical experiments on the first mission would help determine what man could do and how long he could function in zero gravity; the ATM experiments were expected to settle many questions about man's usefulness as a scientist and (it was hoped) gather solar data of unprecedented quality; and the many smaller experiments would yield information useful to space technology and operations. Neither comprehensive nor perfect, the workshop and ATM missions were, scientifically speaking, a start.

MORE ADVICE FROM THE SCIENTIFIC COMMUNITY

While OMSF was hammering out the details of its first post-Apollo project, the President's Science Advisory Committee was considering its answer to the question, "Where do we go in space from here?" Through 1966, 24 members of PSAC's panels on space science and space technology examined the nation's space program. Their report, mainly concerned with broad policy recommendations, also contained several specific criticisms of AAP that were less than welcome just as Mueller was about to go to Congress to campaign for the FY 1968 budget.

The PSAC report, published on 11 February 1967, generally paralleled that of the Space Science Board's 1965 Woods Hole study in endorsing exploration of the moon and planets as the most profitable near-term activity for space research. PSAC, however, asserted that for the 1970s a major goal with a definite deadline was inappropriate. The question was "not so much 'What major endeavor will best provide a basis for expanding our space technology and operational capability?' but 'What are the most advantageous ways to exploit this great capability for the achievement of the national purposes . . . ?' " PSAC favored a balanced program based on the expectation of eventual manned exploration of the planets. This would entail a strongly upgraded planetary program, full exploitation of the ability to explore the moon, qualification of man for long-duration space operations, advancement of technology on all fronts, and the use of earth-orbital operations for the advancement of science, particularly astronomy. Such a program would aim at answering the basic questions that were, in PSAC's estimation, the most challenging goals of space exploration: Is there life elsewhere in the universe? What is the origin of the universe? How did the solar system evolve?[67]

Proceeding from philosophical questions to specifics, PSAC examined NASA's plans and offered some suggestions. Its statement of a broad approach for NASA in the 1970s seemed to coincide with the stated purposes of AAP, but the scientists called for a different emphasis. Any Apollo-Saturn hardware not needed for the first two lunar landings should be used for extensive lunar exploration, not AAP. Beyond currently programmed vehicles, PSAC favored limiting Saturn production to four Saturn Vs per year and some minimum but unspecified number of Saturn IBs. The report compared the Saturn IB unfavorably with the Titan, which the Air Force intended to use to launch its Manned Orbiting Laboratory; the Titan was half as expensive but had the same payload capacity.[68]

The PSAC report revived the issue of a permanent earth-orbiting space station, considering it a requirement for qualifying man for long stays in space. Besides that, a station would provide a place to study the reaction of many life forms to zero gravity and to do research in many scientific disciplines and space technology. The report recommended sending up the first module of a permanent station in the 1970s. As a step toward the functions of a space station, the AAP orbital workshop was acceptable, but with reservations. Citing recent experience with extravehicular activity, the report was dubious regarding the "extensive construction efforts" required by the wet-workshop scheme and argued that such activity might compromise the medical data that should be gathered early in the mission. Rather than risk that, PSAC suggested that NASA should help to fund MOL if that would accelerate the acquisition of biomedical information. It also urged the Air Force to pay more attention to biomedical research in the MOL program.[69]

Astronomy was taken to be the scientific field most ready for exploitation in the post-Apollo period; hence PSAC's astronomy group reviewed the ATM plans—and found them gravely flawed: "From a conceptual point of view this is the wrong way to carry out a man-supported astronomy project in earth orbit." Man's role in AAP was only to operate the instruments, and "it makes no intrinsic difference whether he is 10 feet or 100 feet from the instruments . . . which he manipulates through electrical signals." A microwave control link between the Apollo spacecraft and a free-flying ATM would be better. Still better would be a worldwide communications network, so that the operator could be on the ground. "The heaviest demands on the man [in the ATM project] are to do things which ideally should be done on the ground . . . or by electromechanical systems . . . which do not have to override the angular momentum of the man's movements." The best jobs for a man in orbit were repair, maintenance, and adjustment of the instruments; but because of the short development time, the ATM instruments were not being designed to allow repair and adjustment.[70]

OMSF was trying to please the science community by striving for a 1968 launch of the ATM, but this schedule and the resulting pressure on instrument development drew severe criticism. The period of maximum solar activity was rather broad; by 1970 the frequency of solar flares—one every couple of days at the maximum—would probably still be high enough to justify the mission. NASA's rush to meet a 1968 launch date put unwarranted pressure on two of the instruments and might force compromises in the whole ATM design and operational procedures.[71]

The report concluded that the ATM was certainly not ideal, but its cost was within reason, and to astronomers anxious to fly some kind of high-resolution instruments ATM was a great deal better than nothing. PSAC recommended postponing the launch for a year, however, and using the time to redesign the ATM, get rid of its basic faults, and relieve the hard-pressed instrument makers. The astronomers concluded:

> . . . the proposed mode does not take us down the developmental path which we foresee for earth orbital astronomy. . . . It will very likely demonstrate dramatically the disadvantages of overconstraining the man physically while overburdening him mentally and doing both over a 1-month period with relief only during periods of sleep. Thus, we urge that the mission be conducted primarily for the value of the scientific return and that all mission parameters be optimized to that objective.

And, having talked with some experienced astronauts, the scientists were wary of the complexities of mission operations. They urged that experimenters and mission astronauts work out an acceptable method of managing the experiments during flight.[72] Evidently they had heard that all communications with orbiting spacecraft had to go through the CapCom*—an arrangement which in their opinion could not possibly work for an astronomy mission.

The report seemed to have something for everyone, advocates and critics alike. It was lukewarm toward the workshop mission and negative about details of the ATM, but recommended that both proceed. The report drew little public notice, but when Homer Newell went before the House Subcommittee on Science and Applications he found that Chairman Joseph Karth had read it carefully, underlined many passages, and could quote extensively from it. Karth and Newell engaged in a long colloquy as to whether PSAC favored the solar astronomy mission; Karth argued the negative, but Newell, producing clarifying letters from panel members, read it as a qualified endorsement. George Mueller, perhaps feeling that the best defense is a good offense, took the report's broad recommendations and, without waiting to be asked, showed Congress that AAP was working to achieve them. In response to written questions submitted for the record, he refuted PSAC's criticisms of the ATM.[73]

Less than a fortnight before the PSAC report was published, NASA and the space program were shaken by the fatal fire in an Apollo spacecraft at Kennedy Space Center.[74] Among other consequences of the fire, the impact of the report was masked. Events would outstrip both the report and NASA's reaction to it; and for the next 18 months, AAP would be subjected to stresses far more taxing than adverse scientific criticism.

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* The "capsule communicator"—the only person who talked directly to crews in orbit. Everything passed up by radio had to be cleared through flight operations officers and then communicated by the CapCom.

5

Years of Uncertainty, 1967–1969

Adversity marked the last two years of Lyndon Johnson's presidency. America's commitment in Vietnam grew more expensive, tying down 535 000 troops, taking 24 000 lives, and costing $2 billion a month. Civil disorders and assassinations contributed to the public malaise. The optimism of the early 1960s faded, taking with it much of the spirit of adventure behind the space program. Facing a 1968 deficit of $25 billion, the president accepted substantial reductions in nondefense spending. Though Apollo enjoyed continued support as a commitment made but not yet achieved, post-Apollo programs took sharp cutbacks in funding.[1]

Apollo Applications shared the hard times in full measure. The spacecraft fire at the Cape tarnished NASA's image, raising basic questions about the agency's competence. For some months NASA officials focused their attention on the lunar landing, leaving AAP planners to proceed in an uncertain environment, unsure of funds and largely dependent on Apollo's performance. Successive cuts in AAP budgets forced a retreat from the ambitious program laid out in 1966. Step by step, projected flights shrank and launch dates were postponed. The cluster missions remained two years from launch—a standing joke within NASA.[2]

In late summer 1968, AAP reached its nadir: its most ambitious project, the Apollo telescope mount, was threatened with cancellation. Costs were rising alarmingly, technical problems persisted. The general election brought to power an administration that had yet to formulate a space policy. Then successes in Apollo, particularly *Apollo 8*'s flight around the moon at Christmas, acted as a badly needed tonic. A change of command at NASA helped as well. James Webb had taken care that nothing would interfere—or even seem to interfere—with the lunar landing. His successor, Thomas O. Paine, would have to make his mark with the next program. Paine tried hard to sell ambitious plans for NASA's future. Although his proposals were not adopted, their formulation gave AAP a boost.

In the spring of 1969, the use of a Saturn V to launch a ground-equipped ("dry") S-IVB workshop became irresistible as a solution to the many technical problems of the cluster missions. And when in June the Air Force canceled its Manned Orbiting Laboratory, AAP could be regarded in a new light. The following month, in the afterglow of *Apollo 11*'s lunar landing, NASA announced that AAP would be flown with a dry workshop launched by a Saturn V. Removal of the severe limitations imposed by the Saturn IB, as well as the difficulties of converting a fuel tank into living and working quarters in space, would allow the program to make real progress for the first time.

IMPACT OF THE FIRE

The day before the fatal fire at Kennedy Space Center, George Mueller had referred to AAP flights 1 through 4 as a firm program. But for all his positive tone, some important matters were not settled. Houston still opposed the plan to carry the solar telescopes on a modified lunar module, but had acceded for the time being with the understanding that the concept would be studied further. The center program offices considered a mid-1968 launch for the first mission unrealistic; the new director of AAP, Charles W. Mathews, had already named a committee to define tasks more clearly so that a reasonable launch date could be set.[3]

The committee—Mathews and the three center program managers—baselined* the first four flights in February 1967. Besides agreeing on the essential features of each mission (allowable payload, orbit, and operational modes), the group added a solar-cell array to the Apollo telescope mount and identified numerous tasks required of the centers.[4]

The center program offices spent the month of March assessing schedules and test programs, and on the 30th the committee affirmed that the June 1968 launch date could not be met. A new schedule was laid out, postponing the first launch to December 1968, with the solar astronomy mission following six months later. Even with the time thus gained, two problems remained. Development of the solar telescopes was lagging. Two of the five experimenters believed they could make a mid-1969 launch date, but the other three (High Altitude Observatory, the Naval Research Laboratory, and Harvard College Observatory) needed more time. Second, in the aftermath of the fire the assumption that command and service modules would be available for AAP missions became questionable. North American Aviation was still defining the basic tasks of modifying the spacecraft for the applications missions. Webb, determined that nothing would impede Apollo's recovery, proposed to have a different

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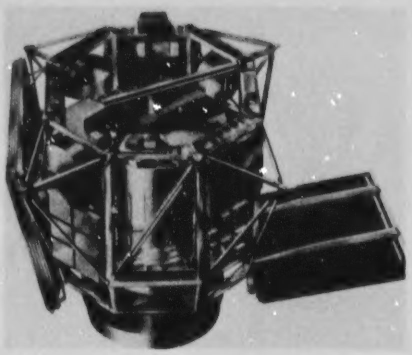
* *Baselining* means defining a point of departure—for hardware, mission, or program—to which subsequent changes are related.



An early version of the Apollo telescope mount. The solar array on the right is partially deployed.

contractor modify spacecraft for AAP so that North American could concentrate on Apollo deficiencies. He also gave the Apollo program director sole authority to divert a command and service module for AAP. The possibility that a new contractor might come into the program made modification uncertain, and little progress resulted.[5]

The accident touched off a period of hectic planning at the Headquarters AAP office. Although the full impact of the fire was not readily apparent, the certainty of lengthening delay forced a series of revisions in Apollo schedules, leading to even more changes in AAP schedules. One major purpose of AAP had always been to give NASA flexibility, and AAP officials still tried to provide for every Apollo contingency; in the event of an early lunar landing or an unforeseen delay, Apollo Applications missions were to fill the gap. Mathews remembered the six months following the fire as a "trying time [when] we developed something like 57 separate program plans for AAP." His program control officer later asserted that the office prepared 55 different plans in a single month. Whatever the number, program documents substantiate an enormous work load.[6]

At Houston the accident pushed AAP into the background. According to Max Faget, "for a year there . . . we stopped arguing about anything except that damned fire." Shortly after the accident, Webb gave George Low the job of managing the spacecraft recovery, and his deputy, Robert Thompson, was left to run the AAP office under adverse conditions. For months on end, paper work was tied down by indecision over reliability and quality standards.[7]

Once Mathews felt settled in his new position, he set out to review AAP plans in person with the centers. At Huntsville, he found von Braun and his AAP manager, Leland F. Belew, mainly concerned about the short deadlines for the solar instruments. At Houston, Gilruth and Thompson questioned North American's ability to provide spacecraft on schedule and doubted that a new contractor could accomplish the AAP modifications on time. They were even more concerned about the number of flights proposed for 1969: a total of 10 manned launches, 6 Apollo missions and 4 AAP flights. MSC's Flight Operations Directorate, however, was preparing to handle no more than 6 manned missions a year. Mathews said that some of the scheduled missions probably would not be launched, but were included to give OMSF flexibility in reacting to program contingencies. MSC officials were not impressed by that reasoning, preferring a realistic schedule that would allow them to make firm plans—a position with which the AAP manager at Kennedy Space Center fully agreed.[8]

Debate over the 1969 schedule became academic that summer as Congress pruned the AAP budget. The fire had diminished confidence in NASA. Don Fuqua (Dem., Fla.), who later served as chairman of the House space sciences subcommittee, thought that its impact was particularly great on congressmen who had been neither strong supporters nor critics of NASA. In more prosperous times the agency might have emerged from the accident without serious consequences; by mid-1967, however, the administration's growing deficit—to which NASA was one contributor—was the biggest issue on Capitol Hill. In a conference committee, Senate and House members concurred in paring $107 million from AAP's $454 million request. The AAP office prepared a new schedule, postponing the first missions by five months and eliminating the use of refurbished spacecraft. In August the appropriation bill set AAP funding at $300 million, nearly $50 million below the authorization level. President Johnson did not oppose the reduction.[9]

Each congressional cut prompted a flurry of planning as the AAP team adjusted the program. One plan avoided further postponement of flights by cutting deeply into funds for experiment definition and payload integration. Another provided more money for experiments and integration by delaying the launches three more months, flying the wet workshop in October 1969. In view of the distinct possibility that more reductions were to come, the AAP office set out a third program based on $250 million. This plan dictated an additional three months' delay, permitting postponement of launch vehicle deliveries and substantially reducing hardware purchases. Mueller considered $250 million the lowest acceptable level of funding. Anything less, he told Seamans, would delay the program's "real start" for another year and would prove wasteful in the long run. Earlier programs, such as the Air Force's ill-fated Skybolt and Dyna-Soar, illustrated the futility of maintaining a high level of design activity without beginning actual hardware development. Mueller concluded, "The normal result is increased cost in subsequent years and often even an inability to bring the program elements to a logical conclusion."[10]

In September Webb ordered some AAP funds transferred to NASA's Office of Tracking and Data Acquisition, leaving $253 million for Apollo Applications in NASA's FY 1968 operating plan. The reduction ruled out concurrent Apollo and AAP flights, for even if launch vehicles and spacecraft became available, NASA could not afford to launch and track them. The first AAP mission was now planned for January 1970, with wet workshop and solar astronomy missions following later that year. The October 1967 schedule called for 17 Saturn IBs and 7 Saturn Vs, a sharp cutback from the 40 launches listed the previous May. Even these figures seemed optimistic, as Saturn IB production was expected to end at 16 vehicles.[11]

The sad fate of mission AAP 1A epitomizes the program's problems in 1967. Because of the spacecraft fire, NASA decided that Apollo missions would carry only those experiments that contributed directly to the lunar landing—a decision that left half a dozen scientists without flights for their experiments. At the same time, AAP planners were struggling with payload weights and crew work loads on the workshop mission. Faced with these problems, OMSF started planning a new mission to inaugurate AAP: a two-week CSM flight in late 1968 to test the lunar mapping and survey system in earth orbit and conduct other earth and space science experiments. The mapping and survey system had been intended to supplement Lunar Orbiter and Surveyor in selecting Apollo landing sites. By the middle of 1967, however, information returned by those two projects was judged adequate. The lunar mapping and survey system seemed redundant and Seamans canceled it in August.[12]

Despite the loss of its principal experiment, AAP 1A moved ahead rapidly, drawing much of its support from the science side of NASA. For the Office of Space Science and Applications, 1A represented the first major effort at manned space science. One OSSA project manager noted after an August briefing (perhaps with some skepticism) that "the justification for the mission appears to be the experiments and not manned spaceflight." He added that "a 14-day flight does not seem to be a cost effective way of obtaining space data for the experiments selected." Nonetheless AAP 1A generated much enthusiasm within OSSA, where considerable effort was spent to accelerate development of the experiment hardware.[13]

By this point AAP 1A was becoming an earth-resources mission, carrying half-a-dozen specialized cameras and four infrared sensors. Mission planning was under way in Houston and at the Denver plant of Martin Marietta, the payload integration contractor. On 25 August MSC published preliminary designs of an experiment carrier that would fit into the spacecraft–lunar module adapter, between the service module and the S-IVB. This module would provide a shirtsleeve atmosphere and enough room for one man to operate the instruments. Martin engineers worked out a flight plan providing six passes over the U.S. each day at an altitude of 260 kilometers in an orbit inclined 50° to the equator.[14]

Apart from its scientific content, the AAP office also valued mission

1A for its training potential. NASA had a tradition of progressively increasing the complexity of missions. Starting AAP with a relatively simple flight would allow attention to be focused first on management and operating relationships. AAP 1A would give Martin Marietta the chance to work with principal investigators and Apollo contractors as well as NASA centers. And if NASA switched to a new contractor for modifying and refurbishing the spacecraft, that firm would find 1A a good training ground.[15]

By late October 1967, AAP 1A planning was in full swing. On the 27th the Flight Operations Planning Group held its first meeting; on 10 November MSC published a project plan; 10 days later the Manned Space Flight Experiments Board approved 10 earth-resource and meteorological experiments. In mid-December engineers met in Denver for a presentation by Martin Marietta on the experiments carrier. Then, suddenly, the mission was gone. At the end of the year, Mathews notified the centers that AAP 1A had been terminated; NASA's financial squeeze was blamed. The decision caused considerable unhappiness in OSSA, where it was taken as more evidence that Mueller was not interested in science. At the AAP office, it seemed to be more work for naught. All the work was not in vain, however; when NASA officials resurrected earth-resource experiments three years later, several 1A sensors found their way into Skylab.[16]

Problems with the Cluster Missions

Technical as well as financial problems intensified as 1967 wore on. The Apollo fire had brought the micrometeoroid hazard (p. 35) into renewed prominence. Early in the new year engineers at Douglas Aircraft Company, the S-IVB contractor, opted for "belt *and* suspenders" when they decided to cover the insulation inside the tank with aluminum foil and to add an external shield to the stage. Their shield design used a thin aluminum sheet, held flush with the S-IVB skin at launch and raised in orbit to stand 13 centimeters off the tank all around. Small particles striking this shield would lose most of their energy before reaching the tank itself.[17]

On 27 February von Braun presided over a wide-ranging meeting at Huntsville to review the meteoroid problem. Engineers from four contractors and two MSF centers examined the data, looked at films of tests, and discussed Douglas's shield design. Clearly aluminum foil suppressed flame propagation and the shield reduced the chance of a serious penetration; as a dividend, Martin Marietta engineers showed that the shield would simplify control of temperature inside the workshop. Neither the weight of the shield (estimated at 320 kilograms) nor its cost (about $250 000) was a serious drawback, and the group concluded that it should be adopted. Studies would continue, however—testing the effect of liquid hydrogen on the foil lining, looking for new and nonflammable insulating materials, even making contingency plans to apply insulation to the outside of the S-IVB if all else failed.[18]

Payload weights were a continuing headache during the year. Early in January the weight of the AAP 4 payload (the lunar module with its solar telescopes) was approaching the Saturn IB's lifting capacity. Two weeks later planners increased the orbital altitude for that mission, reducing allowable payload still more, and MSC imposed larger power requirements, making a bigger solar array necessary. By midyear the ATM experiments canister required an active cooling system; two of the instruments generated enough heat to distort their optical axes beyond permissible limits. At the same time it became clear that heavy shielding would have to be added to film storage vaults to prevent fogging of film by radiation in orbit. Toward the end of April 1967 all of the payloads except AAP 1 were overweight, and design changes in the workshop were creating a weight problem for that mission as well. Rigid metal floors and walls had been added to the wet workshop, and the growing roster of experiments called for more power, to be supplied by adding two sets of solar panels to the workshop. The Apollo command module, undergoing extensive redesign after the fire, was also gaining weight; by midyear it would be 900 kilograms over its design limit.[19]

Mission planning had to deal with another problem; the growing list of experiments required too much crew time. A compatibility analysis in late 1966 showed that assigned experiments needed 313 man-hours, while only 288 were available. The director of flight crew operations at Houston complained that the experiments called for more training time than could be provided. In February, the experiments board found that weight, power, and crew-time requirements demanded a redistribution of experiments among the four AAP missions, a task which necessitated a system of experiment priorities. George Mueller passed this job to Douglas Lord, who reported in July with a scheme that the board accepted without substantial change. Besides the obvious factors (weight, space, crew time, power consumption, and availability of hardware) Lord's criteria included such intangibles as "the value of the experiment to the overall national space effort," which gave the priorities a certain negotiability. By the end of 1967 Lord and Bellcomm, OMSF's consulting systems engineering firm,* had determined the relative priority of all approved AAP experiments; thereafter the assignment of experiments to missions was somewhat easier.[20]

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* Bellcomm was a subsidiary of American Telephone & Telegraph, created to perform independent systems analyses for OMSF and otherwise assist in making technical decisions. Numbering about 200 people, Bellcomm performed many evaluations of Apollo, AAP, and Skylab.

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While the experiments board worried about priorities, program officials at the centers wrestled with more concrete problems. For the first half of the year the Apollo telescope mount provided more than its share: three of the five experiments were behind schedule. During May, schedule changes postponed the ATM mission to mid-1969, easing the development problem for one experiment but giving the other two no relief. At a meeting on 13 July, Harvard College Observatory and the Naval Research Laboratory estimated that their instruments would be delivered much too late for the scheduled launch. The thermal control problems promised to delay delivery still more.[21]

When the problems were discussed at an AAP review on 18 July, a number of solutions were suggested; but postponing the launch to accommodate the experiments was not among them. Upset, the scientists complained to higher management. At the July Management Council meeting, James Webb spoke of the scientists' concern. In AAP's circumstances, he said, it was important to keep the scientific community happy. Nevertheless, only two alternatives were debated: fly what could be delivered on schedule or relax certain requirements on the lagging experiments in the hope of speeding their development. Mueller met with the principal investigators, the OSSA program managers and Marshall representatives in Washington on 27 July to discuss possible courses of action. Harvard proposed to reduce the complexity of its instrument to alleviate production problems; a simpler instrument could gather the desired data, provided the launch went off on time. The Naval Research Laboratory's principal investigator, Richard Tousey, was out of town, and NRL's representative was reluctant to change; but when Mueller declared that a second ATM would be flown about a year after the first and that NRL's original instruments could go on it, the laboratory's spokesman agreed to consider it.[22]

When Tousey returned to Washington, another meeting was called. OSSA expressed concern that schedule pressures were forcing scientists to settle for less than first-quality data—a concern shared by Tousey, who did not want to simplify the NRL experiments. He wanted to hold to the original specifications and concentrate on finishing one instrument; he was willing to take the chance that the other would be left off if it could not be made ready in time. After much discussion, during which OMSF renewed its assurance of a second solar astronomy mission, NRL agreed to accept some reduction in the performance of its instruments and go ahead with both. OSSA's Space Science and Applications Steering Committee endorsed the new arrangement on 14 August. The scientists accepted the change, but the meetings apparently reinforced their belief that OMSF was more interested in flying missions than in doing good science.[23]

Medical experiments also lagged badly throughout 1967. In April, Mueller prodded MSC to get on with building the experiment hardware, citing $1.46 million authorized for that purpose in the preceding six months; of that sum, MSC had committed $876 000 but had obligated only $8000.* Gilruth's response is not on record, but an internal MSC summary asserted that four major medical experiments were in various stages of preliminary work; some were in the final stages of contract negotiation. In any case "Headquarters' concern about alleged schedule slippage seems somewhat inappropriate," because it was self-evident that AAP schedules would have to be adjusted. As those schedules then stood, prototype hardware for use in training was to be delivered by mid-June of 1967—an obvious impossibility.[24]

AAP UNDER INTERNAL ATTACK

In spite of all the problems, Mueller stuck with his plans to fly the basic workshop and ATM missions as scheduled. Some people wondered whether he seriously intended to launch the wet workshop. If he did not, he kept that intention to himself. Difficulties were to be expected, but they had not yet proved insurmountable. Mueller's attitude was shared by Huntsville's managers and working-level engineers. Marshall was fully committed to the wet workshop; von Braun, proud of the center's "can-do" reputation, wanted to preserve that image. If his managers had reservations about the feasibility of the AAP missions, they kept them quiet and bent all their efforts to working the problems.[25]

Officials at Houston had plenty of reservations and did not bother to conceal them from anyone. Since March 1966, when Gilruth had detailed the center's criticisms of AAP to Mueller (pp. 45–46), the Houston center had participated reluctantly in planning the workshop. Perhaps encouraged by Administrator Webb's unwillingness to push AAP strongly, center officials pointed out what seemed to them faults of both conception and execution. From the establishment of the AAP office at MSC, the Houston-Huntsville alliance was an uneasy one. One center saw itself making level-headed, practical criticisms of a poor concept and unsound engineering and management decisions; the other saw a series of roadblocks thrown up to thwart plans rather than cooperation to solve problems.[26]

Houston had no fundamental disagreement with the broad objectives of the missions; the fault lay in the means chosen to carry them out. As Bob Thompson and his staff saw it in mid-1967, the evolution from a group of loosely related earth-orbital flights to the workshop cluster—the "Kluge,"* they dubbed it—had committed AAP to a bad configuration. Thompson said later of the workshop mission, "Had we started with a clean sheet of paper, we would never have done [it] that way." With Gilruth's consent Thompson began assembling a detailed critique of the AAP missions. In MSC's Engineering and Development Directorate, designers began work on a substitute for the wet workshop.[27]

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* Funds are *committed* when agency officials agree among themselves to spend a certain amount of money on a given task. Subsequently, when the agency contracts with an outsider, the funds are said to be *obligated*. The former is a budgeting or bookkeeping exercise, the latter is legally binding.

The Manned Spacecraft Center was not the only source of criticism. The associate administrator for advanced research and technology told Webb in August 1967 that he had no confidence in AAP. Scientific advisory groups, too, found much to criticize. At Huntsville on 11 April the Science and Technology Panel of the President's Science Advisory Committee toured the mockups and reviewed experiment plans. Some members took exception to the proposed allotment of experiment time, feeling that unless the medical experiments were given priority on the first mission the question of man's adaptability to space might be left in doubt. Indeed, other experiments should not be included if they jeopardized the medical objectives. Members of the Space Science Board's Life Sciences Committee, after a briefing in late June, faulted the tight scheduling of crew time. They felt that planning activities down to the minute negated the prime advantages of manned experiments: reflection, judgment, and creative response to the unexpected.[28]

Late in June Robert Seamans toured the MSF centers to see how well Apollo was recovering from the fire. While in Houston he evidently became aware of MSC's doubts about Apollo Applications, for on 26 July he asked Mueller about the validity of the program plans presented to Congress in May, and how much the centers had been involved in the preparation of those plans. Since Mueller had heard other reports of "NASA officials" complaining that AAP plans were irresponsible, he took the time to compose a seven-page defense of the program. Mueller insisted that every OMSF program had been thoroughly coordinated with all elements of his organization—including center personnel. This did not "always mean that there has been a complete meeting of minds," but there was no foundation to charges that anyone was not consulted. He went on to explain the planning and review that had gone into each major AAP decision, concluding that the program had achieved reasonable stability and was realistic in light of current funding levels.[29]

On 29 August 1967 Bob Thompson sent Charles Mathews some recommendations for consideration in the next round of AAP planning—which MSC management was sure would be necessary after congressional action on the budget. Thompson agreed with the broad primary objectives of the program, but felt that the sequence of missions should be determined by mission complexity, rather than by preselected priorities which were, to say the least, debatable. He then outlined MSC's suggestions for AAP flights during 1969–1972.[30]

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* A *kluge* is an assemblage of unrelated parts which, in spite of not being designed to fit together, performs the intended function.

The Houston plan delayed the workshop missions for one year, separated the telescope mount from the workshop missions and delayed it for something more than a year, and ended with a ground-outfitted "dry" S-IVB workshop to be launched on a Saturn V. As a start, MSC proposed to develop a small experiments carrier to fit in the spacecraft–lunar module adapter, capable of carrying a variety of payloads.* One of these would be launched in 1969, carrying the leftover Apollo experiments plus some earth-sensing instruments; several more such missions could be planned as options for the 1969–1971 period. For 1970, Houston's plan called for one 28-day and one 56-day workshop mission, devoted to biomedical and engineering experiments and operations. The telescope mount would be flown in 1971 in a mission of 2–4 weeks duration with the lunar module and telescopes docked to the command module for the whole time. After that, new options might be opened up by the accumulated experience and by changing fiscal resources. MSC saw a number of advantages to this plan. It would begin with comparatively simple missions, progressing to longer and more complex ones. Earth-resource experiments on the first flight could provide an early payoff. Removal of the solar telescopes from the workshop (effectively discarding the cluster concept) resolved the critical problems of payload weight, crew workloads, and the combination of scientific skills required of the crew, besides simplifying operations. Finally, the plan neatly matched the expected availability of Saturn IBs.[31]

Reaction to this proposal at Headquarters was—from Houston's point of view—disappointing. Mueller, unconvinced, directed Mathews to answer each of Houston's objections and proceed as planned. Houston continued the alternate design studies, reviewing them informally with Mathews. A general review of OMSF's future earth-orbiting missions, from AAP to space stations, was scheduled for 18 November; the MSC contingent came prepared to present the case against the wet workshop.[32]

Mathews, Mueller, and Disher opened the review with assessments of the state of AAP. All acknowledged problems, but reflected a basic confidence in the program and the mission plans. Next, Robert Gilruth briefly introduced MSC's presentation, referring to AAP's many questionable aspects and stating concern over the complexity of the cluster missions. He admitted that no single problem seemed insoluble; it was the sum total of technical and managerial difficulties that gave pause.[33]

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* This idea dated back to the original plans for Apollo (see pp. 12–13); it was included in the statement of work for the Apollo spacecraft in 1961.

Bob Thompson then took the floor to present MSC's proposed substitute for the wet workshop and orbital cluster. This was a smaller workshop module, built inside the spacecraft–lunar module adapter and fitted out as living quarters. At its lower end this module could carry any of several specialized experiment modules, such as the solar telescopes or earth-sensing instruments. Less than half as roomy as the S-IVB workshop, the laboratory was nevertheless big enough to house experiments and control panels for major external experiment packages. It could be equipped with solar cells to provide up to 3.7 kilowatts of electrical power. In their mission plans, MSC's main concerns became evident. Their proposed flight schedule called for 10 Saturn IB launches between 1969 and 1972—the same as current AAP schedules. Since the solar instruments would be fitted to the workshop and launched with it, however, the double rendezvous for the ATM mission (p. 38) was avoided and the lunar module–Apollo telescope mount was unnecessary. The first mission would perform the essential medical experiments and collect earth-resources data. A second visit to the smaller workshop would give up to 112 days of manned operation by the end of 1970 and would establish man's ability to work in zero g fully as well as could be done in the S-IVB workshop. In 1971 the solar astronomy mission would be launched without the medical experiments, eliminating the competition for crew time created by that particular pairing. With a revisit, another 112 days of orbital experience and 84 days of solar observations would accrue. For 1972 Houston projected two more missions, but had established no specific experiment plans.[34]

Turning to specific criticisms of the current program—Thompson referred to areas of concern as "warning flags"—he cited the crucial faults of the S-IVB workshop and the lunar module solar observatory. The plan to stow experiments in the multiple docking adapter at launch and move them into the workshop in orbit created unnecessary complexity. Equipment had to be designed both for storage in the adapter and for operation in the workshop. Some of the medical experiments had to be operated in both places. Much of the first four days of the mission was given over to outfitting the workshop, a considerable task which raised MSC's skepticism. Worse, it interfered with crucial medical measurements at the start of the mission—the period of adjustment to weightlessness for which no data were available. The problems of using the lunar module as the carrier for the solar experiments were well known and Thompson merely alluded to them once more.[35]

Thompson next questioned plans for preflight testing of cluster components and contingency plans in case of failure. How could the cluster be adequately tested before launch? What would the mission be worth if the crew could not open the workshop or move into it? The alternate workshop was small enough to be fully tested in its flight configuration, and it did not have to be equipped in orbit.[36]

Touching on AAP's management structure, Thompson said that it created too many interfaces between centers and contractors. MSC's plan would greatly simplify program management, since each center could be responsible for one mission and supervise one prime contractor. He then summed up: the modified lab provided full preflight assembly, checkout, and testing; improved the program's flexibility; gave a better-balanced approach to program objectives; and created better center-contractor relationships. Houston recommended an early study to reevaluate the whole cluster concept.[37]

The next day, Sunday, the group flew to Huntsville to examine hardware mockups and to let Marshall respond to the objections. Point by point the "warning flags" were discussed, and only the MSC representatives found them disturbing. Huntsville officials argued that most of the problems required only diligent application of resources to solve them. Gilruth asserted once more that his center's proposal greatly simplified the program without compromising its objectives and made it easier to achieve with available resources. No one else, however, saw any advantage to switching to new hardware. Von Braun stated that the wet workshop and cluster missions were feasible and desirable. The alternative represented a new program, which would entail at least a year's delay and waste much of the time and money already spent. Kurt Debus, director of Kennedy Space Center, agreed; it was much the same to his center either way, but a change would only waste time and money without offering compensating advantages. Mueller noted that the smaller workshop might be better than the S-IVB, or it might not; but it could be expected to have its own development problems, perhaps as serious as those of the wet workshop. Further, the prospects for getting approval for a new start were extremely poor.[38]

Mueller summed up by asking three questions. Were there compelling technical factors that made the present approach infeasible? Were there compelling reasons why OMSF would not be proud of the results of the current approach? Were there compelling reasons why the present approach could not satisfy program objectives? He asked each person to respond to these questions; everyone present answered no. Mueller then said that the dominant problems were to support the program with adequate manpower at all three centers and to coordinate the total effort effectively. He directed Charles Mathews to see that the workload was equitably distributed so as to assure that the cluster program could be carried out.[39] Houston's challenge had apparently been thoroughly debated and rebuffed.

After returning to Washington, Mueller briefed Robert Seamans on the weekend's discussions. Sporadic consultations among NASA's top managers during the next week convinced Webb to call for a full review. It was held 6 December, beginning with a review of the launch schedule, orbital configurations, and expected contribution of each mission to the objectives of manned spaceflight. After sketching out MSC's proposal, the review examined the technical problems of the workshop and solar astronomy missions. Twenty-one of Houston's concerns were classified as either "problems which have been resolved or are now considered to be resolvable in a straightforward manner" or "major open problems which are common to present or alternate approach." Only four were listed as "major open problems which are peculiar to the present cluster configuration." After reviewing the status of AAP experiments, mission plans, and hardware components, the review ended with OMSF's evaluation of Houston's proposal—essentially the same as Mueller had expressed at Huntsville—and concluded, as had the weekend's review, that the "present approach is feasible and should proceed as planned."[40]

Mueller had made his own decision even before Webb called for the briefing. On 1 December he sent the center directors John Disher's notes on the 18–19 November discussions and a draft of a letter stating that there was no compelling reason to back away from the wet workshop. Mueller made his position quite plain: "I have decided that we should continue with the present AAP approach and request that you proceed accordingly in your implementation of AAP requirements."[41]

Von Braun's initial response reflected intense annoyance at Houston's sudden intransigence. He concurred with Mueller's decision, reproached MSC for waiting so long to raise objections, brought up some "warning flags" about mission AAP 1A and the Apollo spacecraft that Houston had somehow neglected to mention, and commented unfavorably on MSC's alternate proposal. The letter was on its way—Belew was carrying it to Washington—when it was recalled and a much milder version substituted. In it von Braun noted that what MSC saw as danger areas were really "a logical progression of techniques evolved in Gemini and the manned lunar landing." He offered the opinion that judicious trimming of long-term AAP plans could make the first cluster mission cheaper than the FY 1967 estimates had indicated. Finally, he urged Mueller to start studies for follow-on activities. "Our in-house and contractor studies to date," von Braun said, "show a dry Saturn V launched Workshop to be a highly impressive candidate for this next step." He enclosed summaries of several Marshall studies that rebutted MSC's warning flags, point by point.[42]

When Gilruth responded to Mueller's letter he tried once more to convey MSC's basic points. He did not agree that current plans should be followed unless they could be proved totally unsatisfactory. Instead, Gilruth said, "we should have the best program which is practical with the funds made available by Congress." Congress had not specifically approved either the cluster concept or the four projected missions; and since AAP funds for FY 1968 were being cut, a thorough review was desirable even though it might lead to changes in program content as well as schedule. MSC was recommending a complete program review, not pushing a specific alternate configuration.[43]

In a separate letter Gilruth sent along eight pages of comments on Disher's notes spelling out the basic question in the baldest terms: Why borrow trouble? Certainly the S-IVB insulation could be fireproofed, but "none of this would be necessary . . . in a ground fitted vehicle." Even Marshall admitted serious problems in making the S-IVB habitable; "this results from the compromises necessary to convert a liquid hydrogen tank to a living compartment." As for the problems OMSF said could be solved in straightforward fashion, "the necessity to solve them is not required in the alternate approach." The litany was long, but it came down to a single theme: Why do it this way when there is an easier alternative?[44]

Webb evidently heard enough in the 6 December briefing to solidify his long-standing doubts about AAP. On 6 January 1968 he asked Floyd L. Thompson, director of Langley Research Center, to chair a review of alternate possibilities for post-Apollo manned spaceflight. Committee membership reflected Webb's view that it was an agency-wide concern: the directors of the three OMSF field centers, Langley, and Lewis, plus the director of the AAP office in Headquarters.[45] Thompson, an old NACA hand about to conclude a 42-year career in aeronautical and space research, was a respected figure in the agency. He had been associate director at Langley when the Space Task Group, Gilruth's Mercury team, was formed there in 1958. His last extraordinary assignment had been heading the board that investigated the Apollo spacecraft fire. His chairmanship and the high-level membership of the Post-Apollo Advisory Group would assure a thorough review.

The group met four times from late January to late March, visiting each manned spaceflight center.[46] The members reached considerable unanimity about the future of manned spaceflight. The next step should be to make man an effective participant in orbital science. Toward that end, several things could be done between 1971 and 1975: qualification of man for 100–200 days in zero gravity, determination of the need for artificial gravity, and development of the technology to support man in space. The group found the objectives of the early AAP missions generally in line with post-Apollo needs, but thought the program was scattering its shots too widely. The wet workshop was only marginally adequate to obtain the basic information about adaptation to weightlessness. "If unresolved difficulties do persist in the present near-term approach," the report concluded, "the better course may well be to develop plans for ground-assembling the workshop and launching it dry, using the more costly Saturn V, and to accept such schedule delays as will be required by this course." Thompson was realistic about the value of his committee's work; the real service rendered had been to get Houston and Huntsville to look critically at AAP plans and develop a program that both centers could support. On the matter of the wet workshop, representatives of those centers could no longer talk to one another.[47]

Along with the Thompson committee, two other groups were established in the Office of Manned Space Flight to scrutinize specific aspects of AAP. One, chaired by George Mueller, was to review the solar astronomy missions. The other, headed by Douglas R. Lord, deputy director of the Advanced Manned Missions Program in Headquarters, was to define two versions of a ground-outfitted "dry" S-IVB workshop, to be launched on a Saturn V, as possible follow-on missions after the wet workshop.[48]

Lord's group comprised 150 persons at Headquarters and the centers, organized into six task teams. A set of 13 options was considered, from a simple wet-workshop-turned-dry to a highly advanced workshop with a sophisticated package of experiments. Cost estimates were rough, because hard engineering data were scarce; but it appeared that the least expensive option would cost $412 million more than current plans. This workshop would meet the specified launch date, but its experiments offered the least scientific return and the least advancement of manned spaceflight objectives. On the other hand, the advanced workshop with the most productive experiments overshot the desired launch date by more than a year and cost an extra $2.3 billion besides. Considered as a follow-on project, none of the options was appealing. Any of them would compete with the cluster missions for money. The wet workshop made its heaviest budgetary demands in FY 1969 and 1970—just the years when a dry workshop would need heavy financing to get going. Perhaps, as Mueller was telling Congress, logic dictated a progression from the wet workshop to a dry one; but it was money that made the programs go. For the rest of 1968, mention of a dry workshop to follow the cluster missions all but disappeared from official correspondence.[49]

Mueller's LM-ATM Evaluation Board set itself the task of examining every aspect of the astronomy module and mission that had been questioned by any element of OMSF—which amounted to a critical look at Houston's repeated objections to the mission. Since Mueller was occupied with budget hearings, the board did not begin its meetings until early March. The experiments were found to be in good shape, although the scientists doubted that NASA could launch on schedule. The greatest concern was the rising cost of adapting the lunar module for its new functions. Most of the modifications were required to support the crew during rendezvous and docking—that aspect of the mission that MSC, tireless in criticism, had objected to once more. At last Mueller conceded. Manned double rendezvous and docking (p. 73) were dropped and replaced by automatic rendezvous and remote-controlled docking. Houston was content with this. The technique was not yet worked out, but it was something that ought to be developed in any case, and it was preferable to the operational complexity and crew hazards of manned rendezvous and docking. Houston's victory on this point, however, owed as much to cost considerations as anything else.[50]

SHRINKING BUDGETS AND SHRINKING PROGRAM

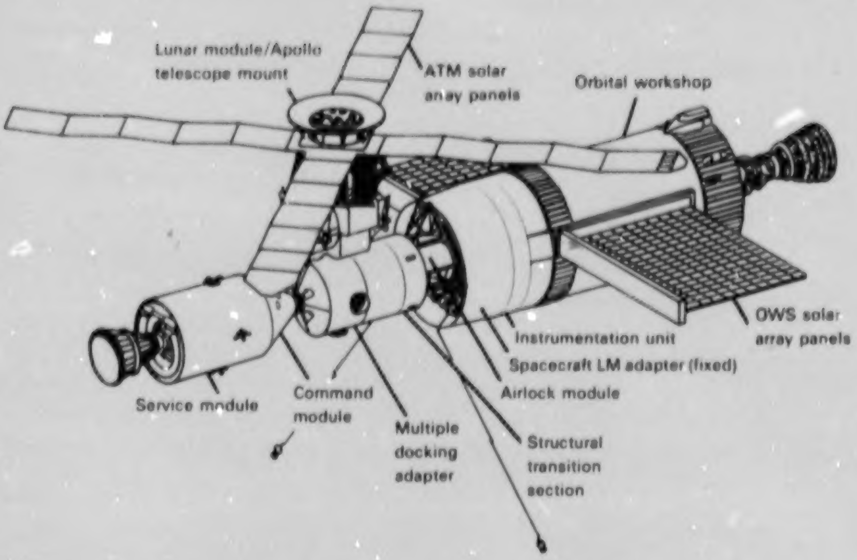
While AAP was being reconsidered within NASA, Congress was pulling the purse strings tighter. NASA's budget request for FY 1969 was the smallest since 1963. OMSF had at one time hoped AAP would benefit from the decline in Apollo costs, down nearly $1 billion in two years; but the troubled passage of the FY 1968 budget had lowered that expectation. The FY 1969 request for AAP was $439 million, 16% less than the submission to the Bureau of the Budget the previous fall and less than half of what had been anticipated in the FY 1968 budget. Nearly half of the $439 million went for new launch vehicles and spacecraft modifications; experiments accounted for another 40%. No new spacecraft was included, and the two Saturn IBs and two Saturn Vs represented only a third of the number Mueller had hoped for. Gone were the second wet workshop, the second solar observatory, the earth-resources mission (AAP 1A), and the lunar exploration missions. In congressional testimony a possible new direction for AAP was indicated by increased emphasis on a Saturn V workshop. Webb told the House committee that the wet workshop was "an interim step toward the Saturn V workshop"; Mueller said that all of AAP's studies to date pointed to "the logic of progressing to the Saturn V launched workshop as the next follow-up step in the evolutionary manned program." In Mueller's view, this workshop corresponded to the orbital station proposed for the mid-1970s by the President's Science Advisory Committee report of February 1967. AAP's budget request proposed to spend $70 million for early work on a Saturn V station—more than twice the sum programmed for the wet workshop or the telescope mount, and more than that allocated for Saturn V production.[51]

Committee members' questions and remarks indicated that AAP was in for rough sledding. William Ryan (Dem., N.Y.), a vocal critic of NASA, questioned Webb about overlap of AAP with the Air Force's Manned Orbiting Laboratory. Webb assured the committee that the two programs did not duplicate each other, provoking Ryan's rejoinder, "Clearly there is duplication." The committee's ranking minority member, James Fulton (Rep., Pa.), questioned the need for additional Saturns in view of the expected surplus from the Apollo program. He feared that NASA was trying to maintain its Saturn industrial base at the expense of new research. On earlier occasions, Fulton had characterized AAP as an ill-defined program, and apparently he saw little improvement. When Mueller spoke of AAP having numerous objectives, Fulton called his remark "the understatement of the year." After Donald Rumsfeld (Rep., Ill.) questioned Mueller about "overlapping" aspects of AAP and MOL, Fulton made several caustic remarks about the wet workshop's layout, questioning among other things the need for a shower costing $300 000. Fulton was critical of several specific details of the design, suggesting that Mueller review the whole thing. "When we looked at your wiring on the Apollo 204," he said, referring to the Apollo fire, "it didn't take much to see that somebody could do the panel wiring better."[52]

In spite of these criticisms, a majority on both congressional space committees concurred with Mueller's assessment that the AAP request would sustain only a minimum program. As Representative Emilio Daddario (Dem., Conn.) put it, further cuts would put NASA out of business. The supporters' main concern appeared to be that the practical benefits of space were insufficiently publicized. Daddario expressed the dilemma while asking Wernher von Braun about NASA's contributions to American technology: "We feel that we have seen great accomplishments . . . and yet . . . how do we, with the great expenditures made, prove that the technology that is developed from it is worth the cost?" The Senate Committee's ranking members, Clinton Anderson (Dem., N.M.) and Margaret Chase Smith (Rep., Me.), expressed similar feelings. Smith concluded, "We have not completely answered the 'why' question—why we should undertake each proposed project from the standpoint of the specific payoffs expected." Such comments were not lost on NASA officials; in March the AAP office reexamined the possibility of early earth-resource experiments, whose benefits were easily understood by the public.[53]

As the hearings proceeded, events conspired to undermine NASA's tenuous support in Congress. The Tet offensive in February threw U.S. troops in Vietnam on the defensive and increased the costs of the war. Two months later, riots following the assassination of Martin Luther King brought pressure for more domestic spending. Congress, preoccupied with the administration's request for a 10% income-tax surcharge and the opposition's demand for a $6 billion cut in nondefense spending, locked onto post-Apollo programs as prime targets for retrenchment. Webb later described what happened to NASA that spring as "a mass walkout of Congressional support."[54]

By March it was obvious that NASA's budget would be cut; the question was, how much? In that somewhat depressing atmosphere, the Management Council and AAP managers met at Kennedy Space Center on 21 March 1968 to assess the program in light of the special studies just concluded. AAP then consisted of three missions using five Saturn IBs. The wet workshop and its crew constituted flights AAP 1 and 2, a 28-day mission to set up the cluster and conduct experiments; these launches had slipped to the second half of 1970. Three months after the first crew returned, a second would go up to the workshop for a 56-day biomedical


Lunar module/Apollo telescope mount
ATM solar array panels
Orbital workshop
OWS solar array panels
Instrumentation unit
Spacecraft LM adapter (fixed)
Airlock module
Structural transition section
Multiple docking adapter
Command module
Service module

The AAP cluster as visualized in the Office of Manned Space Flight at NASA Headquarters, September 1968. MA68-7001.

mission, AAP 3A. The last two launches, in mid-1971, would take up the LM-ATM and its crew on AAP 3 and 4, devoted largely to solar observations. No other flights were defined, but the meeting brought agreement that some earth-looking experiments ought to be studied as possible additions. Planners also decided that a duplicate workshop should be built, to serve as a backup. There was still some talk of a Saturn V dry workshop as the follow-on to the cluster, but everyone agreed that intelligent planning for a dry workshop required information from the wet workshop, and AAP could not afford both.[55]

Mathews told AAP officials at the centers on 21 March that a strategy for slowing AAP work was needed, one that would minimize the cost of current work and defer new commitments while preserving the ability to go ahead. He warned that this would last for several months, since spacecraft modifications, a pacing item, could not begin until the FY 1969 budget was firm. Meanwhile the centers should try to bring all AAP work to the same stage of development. During April the Headquarters program office worked out a holding plan for the rest of 1968, imposing reductions that caused several contracting problems but brought AAP spending down by more than 50%. After the House slashed the AAP authorization on 3 May, Mathews put the holding plan into effect.[56]

The extent of NASA's decline in congressional favor became evident that day on the House floor. During two hours of debate, Representative

Olin Teague (Dem., Tex.) presented a comprehensive defense of the agency's budget, including the $395 million his committee had recommended for AAP. Republicans professed support for space activities, but clearly felt that certain programs should be reduced. Representative James Fulton proposed to cut AAP funding to $253.2 million, the same as for FY 1968. His amendment, along with other reductions, passed by voice vote. Many representatives, like Donald Rumsfeld, regretted the action but thought it necessary to defer NASA programs in favor of others with higher priority.[57]

The Senate space committee considered the House cut too deep and recommended $350 million for Apollo Applications. On the floor, however, William Proxmire's proposal to reduce the NASA authorization by $1 billion failed by only five votes. Senate and House agreed on a figure just over $4 billion, with $253 million for Apollo Applications—about three-fifths the amount requested.[58]

NASA's authorization was still subject to the Revenue and Expenditure Control Act, which required the Johnson administration to refrain from spending $6 billion of its authorized funds. Exactly how this would affect NASA and AAP was uncertain; but on 20 June, the AAP office submitted a program based on $119 million in new funds. Saturn production lines were soon shut down. Webb instructed his management chief not to definitize any AAP contract, because "we have made it clear to the Congress . . . that we would not commit these funds until we [were] sure we were going forward with the AAP in some consistent and cohesive form."[59]

Far from being cohesive, the Apollo Applications Program now seemed about to come apart at the seams. Various expedients were considered to reduce costs: eliminating continuous occupation of the workshop, cutting back the number of experiments, and simplifying the experiment equipment. When solar scientists expressed serious misgivings about their participation under those conditions, NASA officials considered canceling the solar experiments altogether.[60]

The telescope-mount schedule had caused some unhappiness a year earlier when principal investigators from Harvard College Observatory and the Naval Research Laboratory indicated that they could not meet a 1969 launch date. Mueller had resolved matters temporarily by promising a second solar mission and securing the scientists' agreement to simplify their instruments (pp. 89–90). In subsequent funding cuts, the second mission had disappeared and the launch date for the first had slipped to 1971. Understandably, the investigators lost some of their enthusiasm.[61]

On 16 May 1968, Leo Goldberg, director of the Harvard College Observatory, informed Harold Luskin, the new director of AAP, that he wanted to discontinue work on instrument HCO-C, a scanning ultraviolet spectrometer useful primarily for studying large flares during the solar maximum, and to reinstate the original ultraviolet spectroheliometer (called HCO-A). Luskin replied that the ATM would be launched by June 1971 and directed Goldberg to continue work on HCO-C. Current plans were to stop funding for the HCO-A instrument, but NASA would attempt to review the Harvard proposal in June. Luskin's telegram was apparently the last straw for Goldberg, who vented his anger the following day in a letter to John Naugle. He reminded the head of OSSA that Harvard had agreed to fly the simplified experiment as a favor to NASA and with two stipulations: that Harvard would be able to fly its original instruments on a second ATM, and that the first mission would be launched in 1969. Under the latest schedule, however, the more versatile HCO-A would be almost completed when the solar mission was launched; and as Goldberg put it, "Based upon our past experience, I think you will agree that we [can expect] a further slippage of at least two to three months." With the ATM launch pushed back into 1971, two years past the solar maximum, the simpler instrument was no longer worth flying; in fact, the first mission "would be better off without it." Goldberg noted that the ATM was taking up a great deal of the observatory's time, leaving little for developing other interests. He concluded:

> I think it is time to face up to the realization that our participation in the ATM project has been guided more by circumstance and expediency than by the requirements of first-rate science. If we do not jointly take the firm action now to reverse this trend we shall be doing astronomy and NASA both a great disservice.

By now OSSA was siding strongly with the scientists, and after Mueller made some other concessions to the ATM experimenters, Luskin agreed to stop work on the HCO-C and told Goldberg to proceed with the HCO-A.[62]

Most of the other investigators seemed satisfied with the mission even if it flew as late as 1972, believing there would be sufficient solar activity well past the 1969 maximum. But the project was still in trouble. In July, Webb decided that NASA could no longer afford ATM and deleted its funding from the FY 1969 operating budget pending a full debate. Webb opened the review on 5 August with a few remarks about NASA's financial state. The appropriations bill had not yet cleared the Senate; it would be several more months before NASA had a firm budget. Until it did, he was setting a spending level of $3.8 billion and proceeding on a "course of peril." Half a dozen spokesmen then defended the ATM, both on its own merits and because of commitments that had been made to outside groups. Naugle praised Marshall's direction of the project, noting that there were no major unresolved technical problems. Floyd Thompson pointed out the program's technological importance; he thought developments such as the control moment gyroscopes made the mission worthwhile, even if the science failed. Edward G. Gibson, an astronaut-physicist, said ATM would provide the first chance for an observer to apply his judgment to enhance the quality of space science. At last, Webb agreed to continue the ATM, but he was still concerned about winning congressional support. During the next few days, the FY 1969 operating budget was altered to provide $50 million for ATM's further development.[63]

The Wet Workshop Goes Dry

Apollo Applications began the new fiscal year on 1 July 1968 under conditions of real austerity. Most work was on a month-by-month basis, largely under letter contracts—an arrangement normally used only to get a contractor started on a project while a definitive contract was being negotiated. NASA's policy was to avoid letter contracts, which stipulated a level of effort and a limit of compensation; but in the uncertain climate of 1967 and 1968 they became common. By October 1968 there were 15 letter contracts covering AAP projects, including the airlock, the Saturn IBs, and the payload integration work.[64]

Webb had never been an enthusiast for AAP, and as the end of the decade approached and budgets tightened, his determination that it should not get in the way of Apollo intensified. Ever since the spacecraft fire he had concentrated his energies on ensuring the success of the lunar landing; when Congress reduced NASA's budget, Webb reprogrammed AAP funds to meet Apollo requirements. In 1968 he was "putting strong impedance in the system," as the AAP office saw it, by postponing all AAP procurement "unless there is a compelling urgency for the requirement." Apollo Applications, he told center directors in June, was nothing more than "a surge tank for Apollo."[65]

On 16 September 1968, however, Webb announced that he would retire early in October. His deputy, Thomas O. Paine, would take over as acting administrator. Paine had spent 19 years as a scientist and administrator with the General Electric Company before taking his first government job in January 1968. While he and Webb held generally similar views about the agency's future, Paine was more interested in post-Apollo programs. On 4 October he announced to his staff that AAP could proceed with some confidence. Anything done in the next several months to solidify the program would be beneficial; he suggested negotiating definitive contracts. Paine ended the meeting by encouraging his staff to "look for all ways to move faster."[66]

Although the change of leadership helped, successes in Apollo were at least equally important in getting AAP moving again. The October flight of *Apollo 7*, an 11-day mission in earth orbit, redeemed the spacecraft manufacturers and restored public confidence in NASA. For drama, however, nothing that had gone before surpassed *Apollo 8*'s Christmas trip to the moon. By rekindling the country's enthusiasm for spaceflight, *Apollo 8* did much to assure a post-Apollo program. The congressional space committees greeted NASA's budget in January 1969 with a warmth reminiscent of the early 1960s. In April the Nixon administration cut the AAP request by $57 million, but $252 million remained—enough to keep a modest program alive.[67]

When NASA had begun projecting its FY 1970 requirements in the fall of 1968, the mismatch between AAP schedules and prospective funding became severe. Marshall's allocation for Apollo Applications was only about two-thirds what the center needed to meet the current schedule. Houston's plight was worse; Gilruth estimated that AAP required 75% more than MSC was allotted for the program. Under these circumstances a dry workshop to follow the cluster missions seemed a luxury beyond the program's means. In a wire-service story in September, Webb indicated his doubts about post-Apollo plans. "We have no money for additional workshop flights," he said. "So after the first three missions we'll sit back and consider the next step. We could go to an interim step like the Saturn 5 workshop or we could begin planning for a multi-man space station, once again depending on the money available."[68]

When Paine became acting administrator, he too talked about a space station; but the idea got little support. President-Elect Richard Nixon set up a task force on space policy. In January 1969, this group recommended against committing the nation to a large space station. In February, the new president appointed a Space Task Group headed by Vice-President Spiro T. Agnew to make a more detailed study and report to him in September. The new administration was in no hurry to decide NASA's long-term future.[69]

At NASA Headquarters, interest in a dry workshop revived briefly in the first weeks of 1969. With payload weight and stowage space becoming critical for the cluster missions, the weight-lifting capacity of the Saturn V was too tempting to ignore any longer, and the success of *Apollo 8* raised the hope that a Saturn V could be spared from the Apollo program. John Disher presented a plan to use a Saturn V in place of a IB to the Management Council on 5 February; the intent was to cut the cost of the cluster missions by launching all the modules at once. Disher acknowledged that the change would "open a Pandora's box" of technical and administrative problems and that it might be seen as a recurrence of AAP's inability to define a program and stick with it. It would adversely affect costs, schedules, morale, and—worst of all—support from Congress, scientists, and the aerospace industry. When it became apparent in the ensuing discussion that no cost saving would result, the council shelved the plan.[70]

In late April, Mueller told the Senate space committee that the progression from wet workshop to dry workshop to space station now appeared "inefficient and only marginally effective in advancing space technology. . . . the next step in earthorbiting manned space flight must be a new, semi-permanent space station [and] a new low cost transportation capability"—that is, a reusable spacecraft to shuttle from earth to orbit and back. The AAP cluster missions would begin late in 1971 and end some time in 1972. The first module of a space station was expected to go into orbit by the mid-1970s, and in the following 10 years the modular station would be built up to its full size.[71]

Interest in the dry workshop was not completely dead, however. At Marshall, von Braun kept the idea alive; he did not want to risk losing the cluster missions or downgrading the experiment program on account of technical difficulties, and the weight and stowage problems refused to go away. At Houston, Max Faget was getting wind of continued interest in switching to the Saturn V. Pointing out that flying both a wet and dry workshop would be a lamentable waste of funds, he called Gilruth's attention to an MSC study on a dry workshop, implying that reconsideration might be in order. The center AAP managers did not concur. Lee Belew cited "substantial reasons for not changing from the present core program." After a meeting to examine the technical problems facing the wet workshop, Belew saw nothing to justify a change, and Houston's AAP manager agreed.[72]

Crosscurrents were running at Headquarters; Mueller now seemed inclined to change to a dry workshop, but the AAP staff was opposed. Talking with William C. Schneider,* the new program director, Belew got the impression that he was under considerable pressure to change. Schneider felt that the dry workshop would be no cheaper and that a change would delay the first launch by at least a year; Belew gathered that Mueller hoped for yet a different approach.[73]

Belew, reporting these conversations to von Braun, was not unalterably opposed to the change; but he reminded von Braun of a few points that "sometimes get obscured with the light of something new shining in": all contracts would have to be rewritten and renegotiated, Grumman's work on the LM-ATM terminated, and Marshall's manpower assignments completely redistributed. It would be a massive job. The sheer inertia of a program as far along as the wet workshop was formidable.[74]

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* Schneider had taken over Apollo Applications in Dec. 1968, following 18 months as Apollo mission director. Born in New York City and educated at MIT and the University of Virginia, Schneider had joined the National Advisory Committee for Aeronautics, NASA's predecessor, in 1949. He was a veteran of Gemini and his work on *Apollo 8* had earned him NASA's highest award, the Distinguished Service Medal.

Mueller kept the pressure on, at last convinced that the wet workshop was simply not practical and that only a dry workshop could save AAP. The weekend of 3–4 May he presented to center directors and program managers a completely new plan—an integrated program leading from AAP to the space station (and beyond), including three dry workshop flights between 1972 and 1974 that were expected to furnish fundamental information for the design of the station. He charged Schneider with defining the actions required to change the core program in case such a plan were approved. When the group reassembled the following week to hear Schneider's report, Marshall pointed out that an 18-month delay in the first launch was likely. MSC objected that the proposed program would only compete with the wet workshop and the shuttle studies for scarce funds. After a great deal of discussion, the group agreed to consider a different study: a mission using the dry workshop for AAP 2 only, followed by an improved dry workshop that would be revisited four times. Schneider developed a list of specific technical points to be assessed by the centers and called for a report by 15 June on the impact of shifting AAP to a dry workshop.[75]

On 15 May Belew reported preliminary findings from Marshall. With the benefit of several optimistic assumptions, a dry-launched workshop with integral ATM would entail a 10-month delay. Two complete sets of flight hardware would cost an extra $50 million to $100 million, and there would be added costs elsewhere for checkout, launch, and mission operations. The critical factor was getting a quick decision from Headquarters—Belew said it would have to be in 4–6 months. Above all, it was imperative to resist changes further down the line. He conceded that the dry workshop solved many problems and offered more confidence of success; but he pointed out that another major change could be demoralizing. Changes in experiments, mission plans, and program objectives had plagued Apollo Applications from the beginning; and the large payload capacity of the Saturn V would invite new experiments and encourage investigators to improve old ones, with costs going up and schedules slipping all the while. Belew saw no "technical show-stoppers" in the wet workshop program, and it could meet AAP's primary objectives. Considering all the problems that would arise, his center preferred not to change.[76]

There was an alternative, Belew said, which on brief examination looked better: simply shifting the present core program to a dry workshop with no other alterations or additions. This stood a good chance of meeting the current schedule and required little change in the design of the cluster modules. It removed some "very substantial" problems associated with using the S-IVB as a propulsive stage—problems that were giving Marshall more trouble than anticipated three years before. It meant using a Saturn V without taking advantage of its full payload capacity, but that was the very thing that made it attractive: using that capacity entailed too much delay.[77]

On 21 May 1969, while the centers were still working on the impact of the shift to a dry workshop, Mueller presented four options for Management Council to consider as alternatives to the wet workshop. Alternatives 1 and 2 required a Saturn V to put up the cluster and a Saturn IB to orbit the crew and the telescope mount. Alternatives 3 and 4 launched the telescopes along with the cluster modules on a Saturn V and the crew on a IB. In each case there was the choice of using an AAP command and service module, the fuel cells of which could operate for 56 days, or a quiescent CSM, which was powered down after docking, its fuel cells producing just enough power to keep critical systems ready for a quick return to earth if necessary. In the discussion that followed, alternatives 1 and 4 emerged as clear favorites. The first—basically the minimum-change dry workshop that Belew had described to Schneider—was technically inferior, but required fewer adjustments to the program. It was therefore the more salable, because alternative 4 required so many changes that it was, practically speaking, a new start. Mueller told the centers to report to him as soon as possible.[78]

During the following week first reactions crystallized into firm positions. Field centers and Headquarters preferred alternative 4 on technical grounds, but agreed that alternative 1 had the best prospects of acceptance by Paine and Congress. Von Braun's response first reaffirmed his conviction that no change was necessary; the wet workshop only needed some "hard-nosed scrubbing down" to get it on track. The dry workshop, however, was clearly superior. It would allow adding some experiments that had been put off because of weight and volume limitations. Although he clearly preferred alternative 4, von Braun feared that such a major change would lead to unwelcome examination by powers outside the agency.[79]

Schneider presented full details of the four Saturn-V options to Paine on 27 May. Alternative 1, backed by the centers, was estimated to cost about $50 million less over the entire program than alternative 4; but in the crucial fiscal years 1969 through 1971, alternative 4 showed a $200 million advantage. More impressive were the evaluations of probable success in accomplishing AAP objectives. The Saturn V cluster with the quiescent spacecraft outscored all other options and offered the hope of getting significantly more solar data as well. It was clearly OMSF's choice.[80]

Paine, conscious of the need to get Apollo Applications moving toward an attainable goal, concluded that the Saturn-V-launched dry workshop was the best choice available. He wrote to Senator Anderson that NASA was investigating the use of a Saturn V to launch both the workshop and the ATM; in view of the possibility of change, actions on certain contracts would be held up temporarily. Schneider alerted the center program managers on 17 June to be ready with a dry workshop proposal for the July Management Council meeting. He expected alternative 4 to be the only option considered. In preparation for this meeting Schneider scheduled a review at Marshall on the 19th and a meeting with the executives of major AAP contractors the week of the 23d.[81]

Marshall had already started a dry-workshop study, which would not be complete until the end of the month, but by the 19th considerable information was available. This study was based on a configuration in which the ATM was mounted ahead of the multiple docking adapter on a hinged structure allowing the instruments to be swung out 90°. Marshall had produced favorable cost, schedule, and mission success projections for this configuration, which was quickly accepted. At the meeting with major contractors a consensus was easily reached on a launch date for planning purposes: July 1972.[82]

The decision to drop the wet workshop had effectively been made by the end of June. Formalization soon followed. Paine signed the project approval document change on 18 July 1969.[83]

In the meantime, action by the Pentagon had reduced the possibility that Congress might oppose the change. On 10 June the Defense Department announced termination of the Manned Orbiting Laboratory. The decision was made reluctantly, as $1.3 billion had already been spent on the program; but delays had increased the estimated cost to $3 billion, and MOL's continued funding threatened several smaller programs. MOL was a victim of technology as well as tight budgets. Since 1965 the Air Force had made large advances in the use of unmanned satellites for communications, meteorology, and observation, and the Manned Orbiting Laboratory was clearly obsolescent. The cancellation ended the Air Force's hopes for manned spaceflight and brought to a close a decade of political competition.[84]

Only one thing remained: positive assurance that a Saturn V would be available for Apollo Applications. Planners had assumed this as a matter of course, and *Apollo 8, 9*, and *10* had removed all but the faintest shadow of doubt; but until the landing was actually accomplished it was not prudent to suggest that Apollo did not need one of its launch vehicles.* Public announcement of the change was delayed until *Apollo 11* was on its way home. On 22 July 1969, two days after the first lunar landing, the centers were formally directed to implement the dry workshop program.[85]

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* It had taken all of James Webb's power of persuasion to convince Congress and the BOB that Apollo required at least 15 Saturn V launch vehicles, and he would tolerate no suggestion that any could be used for something else. In November 1966 a national magazine quoted von Braun to the effect that if all went well the fourth Saturn V might be sent to the moon in 1968. Webb directed him to back down from that position as soon as possible. Webb to von Braun, 17 Dec. 1966. Until the Apollo lunar mission was successful—and as long as Webb was administrator—AAP could not plan for the use of a Saturn V.

At the same time Schneider specified certain contract actions that were to be taken. Grumman's letter contract for lunar module modifications was to be terminated, as was the Allis-Chalmers subcontract to produce cryogenic tanks for the command-service module. Negotiations with North American on CSM modifications were to be suspended and a manpower limitation placed on that work while a reproposal was being arranged. Marshall was to amend McDonnell Douglas's contracts for the workshop and airlock, redirecting work toward the dry workshop. The impact on all experiments was to be examined and the necessary modifications made. Schneider then laid down a rule intended to avoid another endless parade of changes:

> The basic objectives, tasks, experiments and mission durations will remain unchanged. . . . Only those changes which are dictated by the configuration modification to dry workshop are authorized. . . . All other desirable, but not required changes, will be discouraged and final disposition will be on specific merits.[86]

The decision was welcomed everywhere (except, probably, at those contractors whose AAP work was discontinued), nowhere more than at MSC. The Houston center, in fact, considered itself to have been the prime mover for the change—an attitude that was at least partially justified. Certainly MSC's antipathy toward the basic idea had kept attention focused on the wet workshop's faults; but the combination of technical problems and ever contracting budgets made the abandonment of the wet workshop virtually certain—at least in its ambitious form of early 1969. At Houston satisfaction with the change was moderated only by the delay in making the decision.[87]

Mueller followed the reorientation order with a letter to center directors on 28 July emphasizing the program's priorities. Flight safety was number one, with schedule and cost considerations close behind. The large payload capacity of the Saturn V was useful on both counts; it permitted heavier (and thus safer) components, eliminating the expensive test programs required by less conservative design. The increase in permitted launch weight had its dangers, however, and once more Mueller cautioned that the only allowable changes were those dictated by the change from wet to dry. (The requirement to operate medical experiments in the multiple docking adapter, for example, no longer applied.) No others would be made except by specific authorization of the program director in Washington. Mueller stressed the need to arrive quickly at a firm configuration, avoiding delays and elaboration of the program.[88] Taken with Schneider's telegram of the 22d, this letter established a minimum-change, minimum-cost philosophy that would produce some misunderstandings as the definition of the dry workshop matured.

At Marshall it was realized that the change was probably inevitable and, without doubt, technically desirable. Still, Belew argued that the wet workshop could—and should—have been carried through to a successful conclusion. This attitude might have contained a trace of parochialism, but much more was involved. The dry workshop imposed a great deal of extra work that could not be handled with the manpower available. Marshall had lost more than 600 positions in agency-wide cutbacks early in 1968 and had adjusted its AAP workload accordingly. Now new items of hardware had to be built (the payload shroud and the ATM deployment mechanism) and new analysis, design, and testing had to be done. The integrated launch configuration meant that all workshop and ATM components had to be delivered at once; previously there had been a six-month gap between the two, allowing manpower to be shifted from one to the other. Marshall's assessment showed at least a six-month postponement of launch if all of this work had to be done in-house. Belew accordingly proposed to have several major jobs done by outside contractors, which course was ultimately followed.[89]

RETROSPECT AND PROSPECT

With the decision made and the program defined (except for one set of experiments that would shortly be added), no one had much time to reflect on the program's short but eventful history. AAP had come a long way from the simple proposal of 1965 to get inside an empty S-IVB tank and conduct some experiments. Whether that exercise could have been done, or would have proved worth doing, is debatable; it seemed like a good idea at the time. Probably no one foresaw that this simple exercise would grow into the first major post-Apollo program; but it came along at a time when circumstances forced it into that role.

James Webb, determined to fulfill the commitment to the lunar landing, could see no clear mandate for a space program to follow that achievement. Lacking such a mandate—and he had sought it, without success—he declined to press for a program of his own choosing. Possibly he felt that was for his successor to do. Possibly he felt that a national commitment to another program like Apollo could not be sustained; certainly his deputy, Hugh Dryden, had been sure that it could not.[90]

George Mueller saw an imperative in NASA's founding legislation: to build and maintain an unexcelled capability to operate in space for the national interest. Under that axiom he could not envision allowing the Saturn-Apollo technological accomplishment to be dissipated. If no clear mandate was forthcoming, then utilization of that enormous investment was mandatory until the next step could be defined. When the time came to keep that capability alive, the wet workshop was what Mueller had and he determined to make the best use of it. As circumstances changed, he adjusted his program—postponing launch dates, trimming the experiment program, reducing the number of flights, shifting the work load between centers—to make the best use of his resources. Those resources dwindled alarmingly as AAP was caught in a period of rising inflation and increasing disillusion with sophisticated—and to some, pointless—technology. Mueller was, besides, in basic disagreement with elements of his own organization, especially MSC, where it was thought that the whole program had been conceived hind end foremost. That disagreement, however, kept attention directed at the program's weaknesses and eventually contributed to remedying them.

Webb left NASA at a critical time for Apollo Applications; and Tom Paine, trying for an ambitious space venture after the moon, saw his efforts come to naught in the face of public antipathy and presidential apathy. His attempt, however, probably provided the impetus to make the program's key decision, the change to the dry workshop. Mueller stayed on until late 1969, seeing Apollo through the first two lunar landings and Apollo Applications on the road to success. Speaking at the centers as he left, Mueller expressed confidence that the new, integrated plan would be the basis for NASA's future and that what was to be learned from the dry workshop would be of great importance to everything that would follow it.[91]

The decade of Apollo came to an end as Apollo Applications geared up to carry out the dry workshop missions—only three manned flights now, a 28-day mission scheduled for mid-1972, a 56-day flight in October of that year, and a final 56-day mission early in 1973. Responsibilities were defined and the organization was set up to allow the two major centers to work together, which they would now do with better understanding than before. There would still be plenty of disagreements, but Huntsville and Houston were agreed on the basic purpose of the missions and ready to get on with them.

Part II

Development and Preparations to Fly, 1969–1973

July 1969 was the watershed for Skylab, dividing four years of program definition from a like period of hardware design, fabrication, and testing. The latter period began with a year of changes, including the addition of another substantial scientific program (the earth-resource experiments) and major improvements in the workshop's living accommodations. These changes were not made without difficulty, for they required time and money that were not readily available. A program review in July 1970 established Skylab's final form and content; designs were then stabilized and development began in earnest. Periodic testing and reviews during the next two years assured that all systems functioned together and that the crews could operate them with maximum effectiveness.

Following the first lunar landing, and especially after *Apollo 13* in April 1970, the Manned Spacecraft Center and Kennedy Space Center could devote more attention to their Skylab responsibilities. At Houston, mission planners and training officials devised means to manage the longest manned missions ever flown, while adjusting to the strong scientific orientation of Skylab. Managers and technicians at the Cape prepared for final checkout and launch of the most complex system they had ever handled.

Development of the spacecraft modules, the experiments they carried, and the preparations to launch and operate them are the subjects of part II of this history. Chapter 6 focuses on the program leaders, the problems they faced, and the tools they used to manage Skylab. Chapters 7 through 11 deal with the major experiment programs and the spacecraft components, work managed largely from Huntsville. Houston's preparations for directing the missions are treated in chapter 12, the launch operations at Kennedy Space Center in chapter 13, bringing the story down to 14 May 1973 and the launch of *Skylab*.

6

Managing the Design Phase

In the year following the dry-workshop decision, Skylab moved beyond the bounds of Apollo Applications. Although much of the hardware and many of the managerial practices retained the Apollo stamp, the program took on a new dimension. The name *Skylab,* adopted in February 1970, signified the change of outlook: officials no longer viewed the program simply as a means to use leftover Apollo hardware. Increasingly, it was seen as America's first space station—and perhaps the only one for many years. Several factors contributed to this change. *Apollo 11*'s success allowed NASA officials to give more attention to Skylab, while the Saturn V's greater lift permitted program engineers to expand their plans and make the workshop a better laboratory and home. The program also took on increased importance as it slowly became apparent that Congress would not fund a space station during the 1970s.

MOVING OUT OF APOLLO'S SHADOW

George Mueller's integrated plan of May 1969 listed Apollo and Skylab as NASA's first manned programs of the 1970s. The agency hoped to move out in two general directions: on one avenue Apollo led to further lunar exploration and the possibility of a lunar base; a second route to Earth-orbital operations began with two Saturn-V workshops and proceeded to a permanent, manned space station with a low-cost Shuttle. Major milestones for the decade included:

1972–Earth-orbital operations with Saturn-V-launched workshop
1973–Start of post-Apollo lunar exploration
1974–Suborbital flight tests of Shuttle
    –Launch of second Saturn-V workshop
1975–Initial space station operations
    –Orbital Shuttle flights
1976–Lunar-orbit station
    –Full Shuttle operations

Sometime in the 1980s or 1990s, NASA would establish bases in Earth orbit and on the lunar surface and would land men on Mars.[1]

Paine was anxious to win approval for this ambitious plan in 1969 while public enthusiasm was high. The Space Task Group, a body established by President Nixon to consider America's future space program, provided the administrator an excellent sounding board. In meetings that summer, Paine promoted a manned Mars mission as NASA's next major objective. The task group's September report, *America's Next Decades in Space*, recommended a balanced manned and unmanned space capability and listed three possible programs leading to a manned landing on Mars before the 21st century. The most ambitious option called for a 50-man, Earth-orbiting station in 1980 and the first Mars flight three years later. Funding would reach $8 billion annually by 1976. The least ambitious option cost half that amount and delayed the Mars expedition until the 1990s. The group's chairman, Vice President Spiro Agnew, endorsed the Martian goal enthusiastically, but elsewhere the proposal fell on barren soil. Opposition appeared in Congress and the press, and the Nixon administration approved less than three-quarters of NASA's proposed $4.5 billion budget for FY 1971. That was one-half billion dollars less than the previous year's appropriation and brought NASA to its lowest level of funding in nine years. On 13 January 1970 Paine briefed the press on the impact of the reduction: NASA would suspend production of the Saturn V, cancel *Apollo 20,* delay the initial workshop flight until late 1972, and postpone *Apollo 18* and *19* until 1974.[2]

The following month NASA renamed its Apollo Applications Program. A widespread dissatisfaction with the acronym *AAP** had prompted Paine to seek a new name shortly after the dry-workshop decision. A committee considered nearly 100 names ranging from Socrates to LSD and recommended 8, 4 from mythology and 4 from American history. Mueller forwarded the recommendations to NASA's Project Designation Committee with the comment that a name change "could enhance the public's identification with the program and hopefully provide a more manageable term for everyday use." The committee passed over the recommendations and selected, instead, a name submitted by Lt. Col. Donald Steelman, an Air Force officer on duty with NASA in 1968. *Skylab,* a contraction for "laboratory in the sky," met both of Mueller's objectives as the name was quickly accepted within and outside NASA.[3]

During 1970 Paine continued to press for an expansive space program despite the lack of support from Congress or White House. By June he had to concede that at least one more Apollo mission would be eliminated and that there was no possibility of further Saturn production. Paine hoped that *Skylab* could fly as early as mid-1972. His main concern was to have "a major mission of new significance" by 1976, something more than just another *Skylab*, but he was clearly out of step with the Nixon administration. NASA's interim operating budget, made public on 2 September, provided only $3.27 billion. Two more Apollo missions fell by the wayside; the program would end in June 1972. *Skylab* was supposed to lift off five months later. Paine resigned on 15 September 1970.[4]

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* *AAP* had become the butt of frequent jokes. Opponents referred to it as "Almost A Program" and "Apples, Apricots, and Pears." A cartoon circulated in Houston showed two Martians observing the AAP space station. One, with a puzzled expression, was telling the other: "I don't know what the hell it is, but I think they call it AAP."

The task of defending NASA's budget fell to George Low, the acting administrator. In October Edward David, the president's science adviser, asked Low to evaluate the relative priorities of Apollo and Skylab in the light of further possible cutbacks. Low defended both programs, saying that "to reduce or constrain the scientific returns from Apollo by dropping one or more missions would involve very great losses." But canceling Skylab was even less palatable: "On balance, the weight of evidence seems to favor Skylab over Apollo if a choice must be made." The scientific returns from the single Skylab mission would probably exceed those from an additional lunar landing. America had already benefited from its Apollo investment, whereas canceling Skylab would provide no return. Finally, Skylab could lead to more new options with less risk than Apollo.[5]

David was asking Low to consider reductions in an already austere budget. In a period of 6% inflation, NASA had sought a modest increase to $3.7 billion. The Office of Management and Budget had countered with a $3.3-billion offer, which forced large reductions in the Space Shuttle and nuclear engine programs. Neither Apollo nor Skylab suffered serious cuts; their combined loss of $50 million amounted to less than 5% of the requested amount. Nevertheless, the loss could be absorbed only by slowing the pace of operations. The Office of Manned Space Flight set new launch dates of December 1972 and March 1973 for *Apollo 17* and *Skylab* respectively. When Kennedy Space Center indicated that such closely spaced launches would require overtime, *Skylab* was moved back another month. The budget decision in late 1970 marked the last major change in *Skylab*'s schedule. Thereafter the program moved steadily toward launch.[6]

A SECOND SKYLAB

A second Skylab, under consideration since mid-1969, was a principal casualty of the 1970 budget deliberations. Shortly after the wet-to-dry switch, Charles Mathews suggested that the center program offices begin investigating artificial gravity for a second workshop; the information gained thereby would prove valuable in planning for a permanent space station. In September Mueller's office broadened the study by asking the offices of space science and advanced research to propose other experiment payloads. Guidelines for a follow-on workshop, prepared in November, listed several options—a year-long occupation of a workshop similar to the first Skylab by four three-man crews, the addition of artificial gravity, substitution of a stellar telescope for the ATM, and a more complex group of earth-resource sensors. The additional logistical support and the new experiments would be accomplished with as little change as possible to the workshop's basic configuration. Since the first Skylab's backup hardware would become the second workshop, no major changes could be made on the hardware until near the end of the first missions. The committee set a series of milestones for subsequent studies: a preliminary report on 20 January 1970 to support congressional hearings, a work statement by July, and a preliminary design review in early 1971.[7]

The definition of new experiments continued into the new year. On 7 March, Dale D. Myers, George Mueller's successor,[*] reviewed the progress of preliminary studies with his staff. The group concluded that definition of a stellar telescope had advanced far enough for present needs and that major emphasis in studies should go to artificial gravity and to payloads "providing tangible benefits of general public interest." After the meeting, Schneider asked his center program offices to provide cost estimates for three possible missions: a repeat of the first Skylab, a year-long mission with advanced solar instruments but no major changes to the cluster, and the same configuration with advanced earth-resource instruments in place of the telescope mount.[8]

Answers from the centers conflicted. Houston wanted a firm commitment to a more sophisticated station, even if it meant delaying the first Skylab. Huntsville, fearing that a major commitment to a follow-on Skylab would jeopardize the present program, argued that a year-long mission was impossible without major hardware changes and that artificial gravity would double or triple costs. The most that NASA could afford, in Huntsville's opinion, was a combined earth resources–solar astronomy mission of eight months' duration. Both centers' views were aired at the April meeting of the Manned Space Flight Management Council, along with Schneider's proposals for further work. The council approved additional studies of Skylab II configurations and directed the committee on artificial gravity to present its findings by early May.[9]

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[*] Mueller became vice president of General Dynamics in Dec. 1969. Myers had been vice president and general manager of the Space Shuttle program at North American Rockwell Corp. since June 1969, and earlier president and general manager for the Apollo command and service modules. He had first joined North American Aviation in June 1943 as an aeronautical engineer.

Skylab II studies proceeded that summer in preparation for the FY 1972 budget discussions. Payload weight soon became a serious problem, whose solution might require modifying the second stage of the Saturn rocket. The cost outlook was more disturbing—estimates ranged from $1.32 billion to more than $1.5 billion. Schneider had discussed a second Skylab with officials from the Office of Management and Budget on 31 July and knew money would not come easily. After another review on 31 August, he informed Myers that Skylab II studies had provided sufficient data for planning purposes. Further steps awaited a funding decision.[10]

The decision that fall went against Skylab II. There was some question about its utility; unless the agency made expensive modifications for artificial gravity, the mission would essentially duplicate Skylab I. NASA management found that funding another workshop dictated either a much larger budget or lengthy delays in the Space Shuttle. Although there was strong support for a second Skylab in the House space committee, the Nixon administration was unwilling to underwrite the costs, and NASA did not wish to jeopardize its future programs.[11]

MANAGEMENT TOOLS

During the summer of 1969, the program manager had his hands full managing the first Skylab. From Schneider's point of view, research scientists moved in a world different from that of engineers. He found it difficult to convince them "that you really need the hardware six months before flight." In defense of the scientists, they were probably influenced by their Apollo Applications experience, when schedules had slipped from month to month, allowing almost indefinite time to improve their instruments. Those improvements contributed to the rising costs of developing the experiments, a frequent subject in Schneider's correspondence. Changes to the experimental instruments also made it impossible to "freeze interfaces between experiments and spacecraft," with further damage to budgets and schedules.[12]

Indeed, interface control was one of Skylab's biggest problems. Aerospace engineers used *interface* to describe the common boundary between parts of a space vehicle, such as an electrical or pneumatic connection or a physical fit. Thousands of interfaces on *Skylab* required close supervision to ensure compatible connections. The Skylab program offices managed these interfaces with procedures developed for Apollo: interface control documents and intercenter interface panels.

Interface control documents provided design requirements and criteria for every interface, describing the parameters and constraints under which the common parts functioned. When the interface concerned two items designed by the same center, a level B document applied. If the interface involved two or more centers, a level A document was in order and an intercenter panel assumed responsibility. Following the program manager's approval of a document, each center was responsible for implementing its side of the interface. Huntsville had the additional responsibility of examining both sides of flight hardware interfaces for overall compatibility, while Kennedy Space Center performed a similar role where flight hardware joined ground support equipment. Marshall, with support from Martin Marietta, scheduled and tracked interface control documents and kept the master file. In cases where program managers could not agree on panel action, the matter went to Headquarters for resolution.[13]

The elaborate system had bogged down in 1968 and had threatened to delay Apollo; a similar situation troubled Schneider two years later. At a meeting in July 1970, he noted that incomplete interface control documents were delaying the design of "various Skylab modules and many experiments." Schneider asked Project Integration Director Thomas Hanes to review the status of all documents and recommend ways to eliminate the bottleneck. Little headway was made over the next two months, causing Schneider to direct his program managers to simplify their procedures and get their contractors more directly involved. Hanes's office would work with the centers in developing a better scheduling and tracking system. Shortly thereafter, the centers joined forces in an Interface Working Group; meeting biweekly, the group cleared most of the backlog by early 1971.[14]

Intercenter panels dealt with Skylab interfaces that involved more than one center. Early in Apollo, Gilruth and von Braun had organized panels to exchange ideas and formalize agreements between Huntsville and Houston. When the three centers (Kennedy Space Center joined the arrangement in 1963) approved a solution, the panels would document the agreement. Huntsville found the panels to its liking; in December 1963, von Braun called them "the only effective medium of working out technical problems . . . which cut across center lines." Houston was less enthusiastic. By September 1966 Samuel Phillips, the Apollo program director in Washington, wanted to eliminate them completely. He probably disliked the panels' independence from Headquarters and may have feared that the groups were not properly documenting all of Apollo's interfaces. Nevertheless, in March 1967 Charles Mathews established a panel system for Skylab. His initial order covered four areas where the centers worked together frequently: mechanical, electrical, instrumentation and communications, and mission evaluation. Interfaces on launch operations equipment were to be handled by the Apollo panel for the time being. Two weeks later Mathews added three more panels: mission requirements, systems integration, and systems safety.[15]

By August 1969 there was no question at Headquarters about the need for intercenter panels; with the number of interfaces on Skylab there had to be some formal means of tying the centers' work together. But realignment of some center responsibilities in late 1968 had raised a number of questions about panel relationships and Schneider hoped to resolve them. Huntsville wanted to discontinue the practice of cochairmen in certain key areas and let the responsible center direct panel activities. Houston had suggested doing away with the System Integration Panel since it duplicated the baseline configuration meetings held by Headquarters. There was also support to upgrade guidance and control activities—currently a subpanel of mission requirements—to an independent panel. At a meeting of 5 August, officials decided against wholesale changes in the panel system; instead, the Systems Integration Panel was deleted and a panel for planning tests was added.[16]

Interfaces were part of the larger problem of configuration control. Configuration referred to the various characteristics of hardware: size, weight, shape, connecting points, and power requirements. During the design phase, engineers made frequent configuration changes, many of which affected other parts. The *Apollo 13* accident provided a classic example of a breakdown in configuration control. In 1965, engineers had increased the power used to pressurize an oxygen tank without changing the protective thermostatic switches on the tank's heater. During normal operations the error caused no problem; but an unusual operation, aimed at correcting a different problem some days before launch in 1970, applied the higher voltage long enough to weld the switches shut and damage some insulation. In space, the tanks exploded with near-fatal consequences.[17]

Apollo and Skylab officials attempted to avoid such errors through a series of configuration control boards. These groups evaluated changes to an approved design at one of four levels, depending on the impact of the modification. Level 4 modifications affected neither weight nor performance, such as changing the screws on an instrument from brass to nickel alloy. Level 3 boards dealt with modifications that might affect the schedule or cost of a particular experiment or module but would not affect other hardware; at these levels the centers improved many experiments without Headquarters approval. A level 2 change affected other major hardware and required the approval of the center program manager or his representative. A good example of such a change resulted from a Huntsville inspection by von Braun. Shown plans for a vacuum pump on the lower-body negative-pressure device, von Braun took strong exception: "Right through that wall you've got the greatest vacuum in the universe." Engineers initiated a level 2 change to drill a hole through the workshop wall. When such changes were approved by a level 2 board, the decision was transmitted to the Headquarters office for review. Level 1 actions, requiring Schneider's approval, involved changes to hardware, software, or facilities that might result in inability to meet the operations plan and mission objectives; changes that affected milestones; and changes in excess of $500 000 or that would double the agreed-on cost of an experiment.[18]

Interface control and configuration documents were an important part of the documents system that Skylab inherited from Apollo. Paper work had characterized major projects of the post–World War II era, and Apollo was no exception; indeed, observers facetiously suggested that NASA was trying to reach the moon on stacks of paper. The Skylab Program Office used three types of document to direct the activities of the center program offices. "Skylab Program Specifications" established major functional and performance standards for program hardware. For example, the August 1969 edition set the probability of crew safety at a level comparable to Apollo, with spacecraft parts and systems designed to work 995 times out of 1000 and the reliability of the workshop and launch vehicle put at 0.995 and 0.990 respectively.* "Skylab Program Work Authorizations" identified center responsibilities for more than 50 major end items, among them the one-g spacecraft trainer (Houston) and a workshop engineering mockup (Huntsville). A second list in the authorization document identified over 130 mission milestones, deadlines for specific actions. "Mission Directives" provided detailed statements on objectives, flight plans, space vehicle configurations, experiments, and center responsibilities.[19]

When the paper threatened to drown the program, Schneider asked his managers to review all requirements in the light of three questions. What is the minimum information needed to meet general program responsibilities? What information do you need to meet specific technical responsibilities? What information do you believe other offices will expect you to have available? The Headquarters office undertook a similar review of the documentation requirements it levied against the centers. In spite of NASA's intentions, many participants—particularly scientists—were appalled by the amount of red tape. An investigator working on the human-vestibular experiment at the Navy Aerospace Medical Institute, on first seeing the "Experiment General Specifications," was taken aback. He told Houston officials that the cost of his experiment would increase tenfold and suggested that NASA "build a direct line between Pensacola and Houston, to carry the carloads of paper. . . ."[20]

Of the various management tools used in Skylab, probably the most important—certainly the most prominent—was NASA's formal system of reviews. During Apollo, NASA had developed this system to serve as key management checkpoints during program development. The first three, occurring during the design phases, were:

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* On 27 Oct. 1969 the launch vehicle's crew safety factor was changed to 0.995.

1. Preliminary requirements review—a review of concepts considered and of the concept chosen to meet mission objectives;
2. Preliminary design review—an examination of the basic design conducted early in the detailed design phase;
3. Critical design review—a technical review of specifications and drawings near the conclusion of the detailed design phase.

In Skylab's preliminary and critical design reviews, the module or experiment under review was also examined for its compatibility with other portions of the space station. The next reviews came near the end of hardware development:

4. Configuration inspection—a comparison of manufactured end items (including test equipment as well as flight hardware) with specifications, drawings, and acceptance testing;
5. Certification of flight worthiness—a determination prior to shipment from the factory that flight hardware was complete, qualified, and accompanied by supporting documentation.

Whereas the first five reviews were conducted for each stage, module, and experiment, the last two covered the entire Skylab operation:

6. Design certification review—held four months before launch to certify the spacecraft design for flight worthiness and safety and to assess the design of the launch complex, mission control center, and Manned Space Flight Network;
7. Flight readiness review—held several weeks before launch to validate the operational readiness of the total mission complex.

With these seven milestones, NASA tracked the progress of Skylab hardware from drawing board to launch site.[21]

Since Huntsville was responsible for most Skylab hardware, Lee Belew directed a majority of the reviews. He appointed review board chairmen, scheduled review dates and sites, and ensured that experiment sponsors, contractors, and other NASA offices were represented. Design review teams performed the detailed examination of blueprints, spending much of their time with "review item discrepancies," the principal means to recommend hardware changes. If a qualified individual did not like the location of an experiment or the living arrangements of the workshop, he could submit a discrepancy report. Teams then screened the reports, combining similar ones, approving or disapproving many, and submitting others to the review board for decision. The process was fully documented with center managers maintaining the status of every document as to number, title, category, date for completion, and the individuals responsible for assigned actions. One or two individuals earned a certain notoriety with the center offices by recommending large numbers of changes.[22]

The changeover to the dry workshop touched off extensive reevaluations at McDonnell Douglas plants and in Huntsville. By December 1969 the process had advanced sufficiently to warrant a preliminary design review of the cluster systems. Several hundred NASA and contractor representatives divided into groups to examine requirements for and possible changes to the various systems. Three days of discussion disclosed a number of significant items. Whereas Huntsville and McDonnell Douglas had assumed the astronauts would enter the cluster in vented pressure suits, Houston was planning a "shirtsleeve" entry. The Manned Spacecraft Center also objected to the layout of the telescope mount's control and display console, since astronauts could not monitor it and the panel for the structural transition section simultaneously.* Another problem stemmed from the decision to incline *Skylab*'s orbit 50° from the equator so as to accommodate earth-resource experiments. The change posed problems for engineers working on the thermal control system. To maintain compartment temperatures within the comfort zone when in sunshine, the workshop would have to give off more heat than had been planned. Modifications for this purpose, however, increased the heating requirements during nighttime periods beyond the available power. A decision was postponed pending more detailed studies.[23]

A number of other questions were discussed, but in retrospect the most important decision concerned the electrical power system. From the wet-workshop days, two separate electrical systems had evolved; one of them served the lunar module and the telescope mount. With the elimination of the lunar module, two independent systems no longer made sense, but the "minimum change" dictum in July discouraged any immediate alterations. At the December review, a proposal to combine the separate systems was approved in turn by level 3 and 2 configuration control boards. After weighing increased cost and complexity against the greater probability of mission success, Schneider approved the change. It would develop that, after the accident during launch, this decision would save the mission.[24]

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* The structural transition section, one of four compartments in the airlock, was located at the forward end of the airlock tunnel. It included a heat exchanger, molecular sieve, carbon dioxide sensor, circuit breakers, and several panels.

The cluster systems review generated a number of actions over the next few months, among them a detailed study of the power and thermal systems, reorientation and relocation of the ATM's display panel, modifications of the multiple docking adapter including the retention of a side port for emergency docking, and a thorough study of the ATM's computer software. The work proceeded under a tight schedule which received attention when Schneider and Belew met with the airlock team in St. Louis on 10–11 December. Schneider was particularly worried about the short time between critical design reviews and the delivery of flight hardware. If major problems arose at the reviews, contractors would probably not meet their delivery dates. Accordingly, Schneider wanted all personnel involved in a design to review and critique their areas of responsibility regularly. Managers were to stress content "rather than extensive formal preparation of presentation material."[25]

In January, Schneider pressed Belew to hold a series of reviews the following month, much like the December meeting in Huntsville. The program director was concerned that "failure mode and effects analyses"* were lagging and would delay the rest of the design work. He considered reviews in this area mandatory, while follow-up reviews on the electrical power, environmental control, and attitude-control systems were highly desirable. Belew did not share Schneider's concern about work on failure modes. Although formal documentation was usually not available, Huntsville's designers and analysts were working closely together, and Belew had taken steps to have the failure mode documents available 90 days before the critical design reviews. As for the other reviews, Belew wanted to avoid "large, relatively inefficient reviews which would in fact impede much activity which is already planned."[26]

Belew preferred to use monthly crew-station reviews, agreed to by the center managers in December. In these meetings, astronauts walked through mockups of flight hardware to ensure that the design met operational requirements. Attendance was held to a minimum; NASA and contractor representatives had sufficient rank to make immediate decisions on matters not involving large cost or schedule delays. The next meeting of a configuration control board then confirmed their decisions. When members of the review team disagreed, they could appeal to the board. However, review teams were encouraged to resolve matters among themselves. The reviews used engineering mockups at each contractor plant, and each mockup included appropriate interfaces. (Thus the airlock mockup in St. Louis had a workshop hatch and adjacent portions of the docking adapter.) Belew thought crew-station reviews provided a "more continuous effort of responsible parties, concentrated nearer the working level." Judging by Belew's weekly reports in early 1970, Skylab was one review after another. At contractor plants in St. Louis, Denver, and Los Angeles, teams of 40 to 50 engineers and astronauts participated in crew-station reviews on the major modules. In between these meetings, smaller groups coordinated daily changes.[27]

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* In "failure mode and effects analyses," all imaginable hardware failures were listed. Engineers examined methods to detect and eliminate each shortcoming through redesign, removal of low-reliability parts, or operational procedures to work around (bypass) the difficulty.

Reviews of 70 Skylab experiments were an additional burden for the program offices. Managers were required to certify each review as to completeness and adequacy of documentation within 60 days of completion. Despite attempts to tailor the reviews to the importance of the experiment, based on crew safety and mission success, the centers fell behind schedule. In July Schneider took the managers to task for 27 uncertified reviews.[28]

Design work climaxed in mid-1970 with critical design reviews of Skylab's principal hardware. Each lasted nearly a week and involved upwards of 300 NASA and contractor engineers. Review boards considered an average of 200 discrepancies on each module and although most of the proposals were minor, collectively the changes could delay *Skylab*'s launch by several months.[29]

THE PROBLEM OF CHANGES

Changes posed the biggest problem for Skylab managers during the first two years of program development. At the time of the dry-workshop decision, Headquarters had decreed "minimum change." The restriction was short lived, however; by October 1969 a dozen major changes were under consideration, among them a 120-day mission for the final crew, an earth-resource package of experiments, an orbit inclined 50° from the equator, operation of the solar telescopes in an unmanned mode, and the addition of a teleprinter. That month Schneider approved a series of physical modifications to the workshop including the addition of a side access door and a window, the reversal of the "floor" equipment to the new, hard "ceiling," and a new wardroom combining the sleep compartment with the food management area. At Huntsville, the center responsible for keeping all of that hardware on schedule, Belew protested the extent of the changes, stating that they constituted a new workshop mission. He estimated the changes would delay the schedule by six months and add $100 million to the costs.[30]

Indeed, Schneider had not given the centers much slack. Two weeks after the dry-workshop decision, he announced a working schedule with a flight-readiness target of March 1972. By setting his deadline four months ahead of the official launch date, Schneider sought to ensure against unforeseen problems. Huntsville's reaction in August was positive; the working schedule appeared feasible with the possible exception of the solar telescope mount. Houston officials were less sanguine. Kenneth S. Kleinknecht,* who would soon replace Thompson as Skylab manager, noted that "AAP schedules are fluid and are being established before full definition of either the workshop or the CSM." He saw no slack left in the schedule for problems or changes and concluded, "with such an approach, schedules cannot be met." In December—before the changes had been fully assessed—Belew reported that his contractors were under an "extremely tight schedule." The centers gained breathing room in January 1970 when FY 1971 budget cuts forced a four-month slip in the working schedule; but by May, Houston was pushing for further delay and some items were three to four months behind schedule.[31]

As design work proceeded, NASA officials debated the merits of further changes. On 27 March 1970—shortly after a major decision to modify the urine processing—Dale Myers announced that Skylab could accept no more experiments, since "hardware development activities have reached the stage and maturity where any significant additions or modifications will cause a schedule slip." In May, however, Houston sought further changes in habitability aspects of the workshop. This brought loud protests from Huntsville and led to a major program review 7–8 July. The review team approved many of the proposed changes, while reaffirming the launch date of July 1972. The director of Marshall wrote Headquarters that the new changes would eliminate all slack from Skylab's schedule. If modifications continued, Huntsville would be unable to maintain either schedule or budget. The following month, he urged Gilruth to assist him in reducing program changes since the limitations of the Skylab systems "are now being reached, or in some cases nearly exceeded."[32]

Correspondence between Belew and Schneider that summer pointed up the problem of funding, which the changes exacerbated. On 17 July Belew indicated that Huntsville would need more money if the center was to maintain the schedule. Schneider replied that there were no unallocated Skylab resources, nor was it prudent to expect more. He asked Belew to devise a way of meeting his program objectives within present resources. The plan was to include specific manpower restrictions for major contractors and in-house personnel. From the subsequent review, Belew concluded that the Skylab schedule and resources were, indeed, incompatible; Marshall needed $285 million in FY 1971 funds, nearly $50 million more than the intended allocation. Meanwhile, Schneider had found an additional $25 million for Huntsville, halving Belew's deficit. The Huntsville manager proposed to spread the shortfall among all his major projects, bringing each down about 10% below desired funding. This looked all right until early October, when McDonnell Douglas reported that its allocation would delay workshop delivery by two months, removing all the schedule margin from the official launch date. On 7 October Belew reported that unless NASA controlled changes more stringently, it would not make a 1972 launch "at any price." During a teleconference on the 13th, Schneider added $12 million to Huntsville's funds so that Belew could speed up his contractor's work. (The sum eventually came from Houston's allocation.)[33]

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* Kleinknecht had been manager of the command and service modules in the Apollo program since Feb. 1967. With a B.S. in mechanical engineering from Purdue, he had gone to work for NACA-Lewis Research Center in 1942. At the Flight Research Center, Edwards AFB, Calif., he worked on the development of the X-15. At the Manned Spacecraft Center, he managed the Mercury Project Office and was deputy manager for Gemini.

Scheduling pressures eased in September 1970 when Schneider dropped the idea of a working launch date, set four months ahead of the official schedule. At Houston, Kleinknecht was particularly pleased by the end of the two-schedule policy:

> When people know that they're working to a schedule that nobody expects to make, you can't keep them motivated and people start playing games with the schedule, too. . . . The only way to run a program is to have a do-able schedule; it can be ambitious, [but it must be] one that everybody can focus on and feel that if he does his part of the job we will remain on schedule.

Schneider attempted to retain some cushion by scheduling hardware into the Cape three months before the required date.[34]

The critical design reviews recommended many small modifications, but few large changes were proposed after the fall of 1970. As Schneider noted on 15 December: "The flexibility to incorporate changes without impacting the launch date and critical program resources has passed and each proposed change has to be considered on the basis of Skylab systems impact and how each change can impact other aspects of the total Skylab program." Although Huntsville had opposed many of the proposed changes in 1969 and 1970—largely because of the impact on schedules and cost—after the mission the consensus was that the changes had enhanced the program well beyond their cost.[35]

THE PROBLEM OF REENTRY

One change that had been debated and ruled out was providing for controlling the reentry of the orbital cluster when it finally came back to earth. At nearly 75 000 kilograms, *Skylab* would be the heaviest object ever placed into orbit, and its high orbital inclination would take it over most of the earth's surface. The eventual reentry of the workshop—or large pieces of it—posed a problem of a magnitude that NASA had not previously had to face. For years the hazard of falling space junk—spent booster stages, spacecraft, or satellites—had existed, and treaties spelled out the responsibility of spacefaring nations for injury or damage caused by their vehicles. Starting in late 1962 the manned spaceflight centers and their contractors had studied the survival of earth-orbiting vehicles and means of predicting their impact points or controlling their reentry. Prediction was difficult, and providing for controlled reentry imposed severe weight penalties. All the studies, however, indicated such a small probability of human injury that NASA management accepted the risk, in spite of White House and State Department fears of possible diplomatic repercussions. Some measures were taken for payloads that seemed to create abnormal hazards. The unmanned spacecraft used on the test flight of *Gemini-Titan 1*, and the 17 590-kilogram payload of SA-5 were both modified structurally so that they would break up into small pieces on striking the atmosphere.[36]

No such solution was possible for *Skylab*, however, and early in 1970 Administrator Thomas Paine called for a review of the reentry hazard and an assessment of possible engineering changes to minimize it. The resulting study considered the S-II booster stage, the four segments of the payload shroud, and the orbital workshop, concluding that there was 1 chance in 55 that a fragment of *Skylab* would strike someone.[37]

As for countermeasures, the only sure solution was to add retrorockets and control systems so that ground controllers could bring the fragments down in a preselected location—preferably a wide stretch of ocean. For the S-II stage, the study group calculated, such systems would weigh about 9000 kilograms and would cost perhaps $10 million; for the workshop the weight penalties were similar and the costs even higher. The added weight of these systems would severely tax the attitude-control and electrical power systems, requiring extensive redesign and adding months to the schedule.[38]

The study group concluded that NASA should accept the rather small risk, which was somewhat less than that expected from all other sources—meteorites and space junk already in orbit*—during *Skylab*'s expected lifetime. The cost of reducing the risk by 50% was extremely high. The group recommended, however, that criteria for acceptable risk should be established early in future programs, so that planning and development could incorporate them.[39]

These conclusions were corroborated in all important respects later in the year by a study performed for Marshall by Lockheed Missiles and Space Company. Lockheed's experts concluded that 306 pieces of the

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* A 1972 study determined that 547 spacecraft, 282 rocket bodies, and 1931 fragments were orbiting the earth; 1911 of them had been launched by the U.S. and 849 by other countries. Between 1967 and 1972, 826 pieces of space junk had reentered the atmosphere; of these, 184 were American (56 NASA and 128 DoD). At least 31 fragments had been recovered and tentatively identified.

Skylab cluster, totaling 22 600 kilograms, would survive reentry. The largest piece would be the film vault, as big as a large executive desk and weighing as much as a compact car. Lockheed's study did not assign a significantly higher risk figure than previous studies, however.[40]

In late November 1970 Dale Myers forwarded formal recommendations to Acting Administrator George Low. These largely agreed with the conclusions reached 11 months earlier—namely, that the risk was small enough to be accepted in view of the weight and cost penalties imposed by redesign. Low accepted Myers's recommendations and ordered the Office of Manned Space Flight to work with the Office of Public Affairs and the Office of International Affairs to develop a plan for the public affairs aspects of the *Skylab* reentry problem.[41]

The first phase of program development ended in late 1970 with the completion of design work. In 16 months Skylab program offices had defined relations with Apollo, organized management tools, steered the cluster through its design phase, decided what to do about the reentry problem, and begun preparation for tests. *Skylab*'s appearance and objectives had undergone considerable modification, but the period of major change was over. Ahead lay hardware fabrication and tests.

7

Living and Working in Space

Skylab's experiments and spacecraft systems received the best engineering attention NASA and its contractors could give them, to make sure they were functional, efficient, reliable, and safe. But the workshop was not just a workshop; it was home as well, where crews would be confined for as long as three months. Making it a pleasant place to live might be important in making it efficient.

George Mueller became concerned about the amenities of living in space in 1967 but, recognizing the difficulties inherent in the wet workshop, did not press the point strongly. Once those difficulties disappeared, however, he and the Headquarters program office put steady pressure on the field centers to improve living conditions in the dry workshop. Not only was it important for *Skylab* crews to have something better than a boiler room to live in, there was also the chance to learn something about living conditions in orbit for the benefit of future programs. Nobody knew much about housekeeping in a space station. Mueller found willing allies in Houston, where man had always been the principal concern; but Huntsville had to be convinced. Constrained by schedule, budget, and resources, Marshall resisted the extensive changes that Headquarters and Houston proposed. Improvements in *Skylab*'s living conditions were debated for a year before being accepted as essential to mission success.

HABITABILITY OF EARLY SPACECRAFT

The three cluster modules enclosed 347 cubic meters of space—more than 150 times as much as a Gemini spacecraft, nearly 60 times that inside the Apollo command module. Over two-thirds of this was in the liquid hydrogen tank, 6.6 meters in diameter and 8.9 meters high, which became the orbital workshop. Here the crews would eat and sleep and do much of their work.

Early spacecraft had been designed to be operated, not lived in. Weight and volume limitations in the Mercury and Gemini "capsules"—the epithet, though despised by crews, was apt—meant that only the bare requirements for protecting and sustaining life could be provided. Michael Collins, pilot on *Gemini 10,* compared the two-man Gemini craft to the front seats of a Volkswagen. That tiny space was home for Frank Borman and James Lovell for 14 days on *Gemini* 7. Borman later admitted they had made it on sheer motivation; after accomplishing their prime purpose, the first orbital rendezvous of two spacecraft, the rest of the mission had been a test of endurance.[1]

The Apollo command module, though just over twice the volume of Gemini, was still primarily a functional spacecraft. Some improvements made it a bit more pleasant—hot water, for example—and its extra space gave the crew of three some freedom to move around and exercise stiff muscles; but few concessions were made to mere comfort. For the most part, astronauts accepted whatever discomforts were inherent in their spacecraft, unless they interfered with performance; what mattered was accomplishing the missions. Quite a lot of minor inconvenience could be tolerated by a man on his way to the moon.

When early planners looked ahead to orbiting space stations, their attention was devoted to problems much more pressing than crew comfort. Of 41 papers presented at a space station symposium in 1960, only one addressed the question of making the station a pleasant place to live. This paper noted that operating an orbiting station would be much like keeping a lighthouse ("a rather humdrum task") and discussed some of the factors that would have to be improved so that people could be induced to go into space "after the romance has worn off." Some of these factors were intangible, said the author, but they were no less important for that. Nine years later the situation had changed little. Spacecraft technology still occupied the engineers' attention, while the questions of everyday living were left for someone else to look after.[2]

Habitability, livability—or whatever name is given to the suitability of the environment for daily living—is, as one NASA designer remarked, "a nebulous term at best," one not usually found in the engineer's vocabulary. Besides factors within the engineer's usual responsibilities, such as the composition and temperature of the atmosphere and the levels of light and noise, habitability also encompasses the ease of keeping house, the convenience of attending to personal hygiene, and the provision for exercise and off-duty relaxation. Experience and intuition both suggested that these factors would become more important as missions grew longer. Looking ahead to space stations, NASA designers needed basic information on these problems of living in space, as George Mueller had told congressional committees more than once.[3]

HABITABILITY OF THE WET WORKSHOP

The earliest spent-stage proposal had not called for using the S-IVB as round-the-clock living quarters, although it had provided for testing some habitability features. As planning progressed through 1966, however, the idea of setting up housekeeping in the spent stage took hold. In September of that year the Manned Space Flight Experiments Board approved an MSC-sponsored experiment entitled "Habitability/Crew Quarters," having the objective of obtaining design criteria for advanced spacecraft and long-term space stations. Houston's presentation of this experiment included sketches showing the workshop divided into compartments by means of fabric panels, which were stowed at launch in canisters mounted on the airlock trusses.[4]

Marshall too had an experiment that included crew quarters: the workshop itself, on the books in the early days as "Experiment M402, Orbital Workshop." For a while the two overlapping experiments were a point of contention between the centers. Crew quarters were obviously a part of the workshop, which, as Marshall read the Lake Logan agreement of 1966, was a mission module belonging to Huntsville. Houston saw habitability as an experiment with a principal investigator at MSC; besides, it logically came under the jurisdiction of MSC's Crew Systems Division. For over a year the two program offices could not agree on what the habitability experiment was or who had charge of it. Finally Charles Mathews issued an order giving Marshall overall management and integration responsibility for "Experiment M487, Habitability/Crew Quarters," while dividing a list of specific hardware items between the centers. Houston kept the life-support systems, along with food management, waste management, personal hygiene, and sleep restraints; Marshall got the rest, which was mostly the structure, plumbing, and wiring of the crew quarters.[5]

Houston could do very little with its share of the workshop duties in 1967. It was not stated center policy, but everyone understood that Apollo Applications had low priority until Apollo was back on track. The fact was, as one MSC division chief said, "if we didn't get the Apollo program done, a lot of the discussion about AAP [would be] academic." It was well into 1968 before the center could spare any manpower to work on projects such as habitability.[6]

At Huntsville meanwhile, Belew's engineers went ahead, using their own ideas plus whatever help MSC could give. By early 1967 the plan to use fabric curtains to subdivide the workshop had been dropped in favor of metal partitions installed in the tank before launch. These were fabricated of aluminum, machined into a triangular grid pattern that did not obstruct fuel flow; folding sheet-metal partitions made it possible to close two of the compartments during occupancy. The workshop ventilation system, a set of fabric panels forming an annular space next to the wall, was also put in place before flight. During activation of the workshop the crew would install fans to circulate the air and rig a curtain under the floor to form a mixing chamber for the circulating atmosphere.[7]

Houston's first look at Marshall's detailed plans came at the preliminary design review at Huntsville, 8-10 May 1967. Design details were necessarily tentative, but it was evident that Marshall had paid very little attention to habitability. Houston, however, was more concerned with fire hazards than anything else, and about the only comment concerning living conditions dealt with the temperature control system.[8]

During that summer and fall George Mueller took a strong interest in the workshop, especially the layout of the living quarters. After examining the mockup in July, he suggested adding a second floor (a ceiling on the crew quarters) to provide extra work space; but since that would have aggravated a serious weight problem, his suggestion was not adopted. Later he proposed installing two grids 2.6 meters above the liquid-oxygen-tank dome, creating two compartments with floors back to back. This became the accepted configuration until July 1969.[9]

Looking at the mockup, Mueller was appalled by the barren, mechanical character of the workshop interior. "Nobody could have lived in that thing for more than two months," he said of it later; "they'd have gone stir-crazy." Expressing this concern to Lee Belew and Charles Mathews, he suggested that an industrial design expert be brought in to give the workshop "some reasonable degree of creature comfort." Late in August, Mathews wrote to Belew recommending action on Mueller's suggestion and offering the names of two commercial firms. Marshall arranged for Martin Marietta, the integration contractor, to engage an industrial design consultant on subcontract. His task would be to provide "comments and recommendations based on the latest industrial design concepts, relative to floor plan arrangements, color schemes, lighting, noise levels, and all other factors relating to human comfort in confined quarters." A two-month study beginning on 1 December 1967 would evaluate the wet workshop.[10]

CONTRIBUTION OF INDUSTRIAL DESIGNERS

For the habitability study, Martin Marietta chose one of the best known industrial design firms in the world—Raymond Loewy/William Snaith, Inc., of New York. Loewy, a pioneer of industrial design in the United States, had worked on functional styling for a variety of industrial products for forty years, besides designing stores, shopping centers, and office buildings. Approaching his 75th birthday in 1968, Loewy had reduced the scope of his own professional activity somewhat, but he took a personal interest in the workshop project. Early in December 1967 he and Fred Toerge, the firm's vice president, visited all the AAP contractors' plants, ending their tour at Huntsville with briefings on the program and an examination of what Marshall had done to that point. Loewy and Toerge then stopped off in Washington to discuss their impressions (which were mostly bad) with Mueller, Mathews, and other AAP officials.[11]

Loewy/Snaith produced a formal report in February 1968, citing many faults in the existing layout and suggesting a number of improvements. The interior of the workshop was poorly planned; a working area should be simple, with enclosed and open areas "flow[ing] smoothly as integrated elements . . . against neutral backgrounds." While they found a certain "honesty in the straightforward treatment of interior space," the overall impression was nonetheless forbidding. The basic cylindrical structure clashed with rectangular elements and with the harsh pattern of triangular gridwork liberally spread throughout the workshop. The visual environment was badly cluttered. Lights were scattered apparently at random over the ceiling, and colors were much too dark. This depressing habitat could, however, be much improved simply by organized use of color and illumination. Loewy/Snaith recommended a neutral background of pale yellow, with brighter accents for variety and for identifying crew aids, experiment equipment, and personal kits. Lighting should be localized at work areas, and lights with a warmer spectral range substituted for the cold fluorescents used in the mockup.[12]

Martin Marietta presented these findings along with some of their own recommendations at Huntsville on 28 February, urging immediate attention to the consultant's recommendations. The color scheme was of first priority; it would not be easy to find a finish that could stand immersion in liquid hydrogen, and there was not much time to look. The floor plan should be revised as soon as possible. Loewy recommended creating a wardroom—a space for eating, relaxing, and handling routine office work—and Martin's engineers concurred. Better yet, the floor plan should be made flexible by the use of movable panels, so that different arrangements could be tested. Evaluating a single layout was not a good way to acquire information about the design of space stations.[13]

These suggestions were received at Marshall with a certain amount of perplexity. To the extent that they had considered styling and interior decor, Huntsville engineers had assumed that Douglas, an experienced builder of commercial aircraft, would tend to them. And since none of the astronauts who had examined the mockups had attached any importance to such things, Marshall had assumed that they were of small concern. Fairly soon, however, program officials recognized that there was something to the Loewy/Snaith study and began to work on the color scheme. Because of the liquid-hydrogen problem, this turned out to be a major headache for the duration of the wet-workshop plans.[14]

Mueller was pleased with Loewy/Snaith's work, and a new contract was drawn up engaging the firm through 1968. By now MSC was taking greater interest in the crew quarters, and the new Loewy/Snaith contract specifically provided that the consultants would work with the principal investigator for MSC's habitability experiment.[15]

In June 1968 a new principal investigator was appointed for experiment M487 at MSC: Caldwell C. Johnson, chief of spacecraft design in the Advanced Spacecraft Technology Division.[16] Caldwell (the first *l* is silent) Johnson was a tidewater Virginian who had joined NACA in 1939, two years after graduating from high school. He had been a member of Gilruth's design team since Mercury days and had worked on Apollo from 1961 to 1963, when he became assistant chief of the Advanced Spacecraft Technology Division. Johnson was an idea man, whose forte was producing novel design concepts for all kinds of systems; he took little interest in overseeing hardware development. His new assignment probably reflected Gilruth's desire to have an experienced designer do an end-to-end job on the workshop's crew quarters.[17]

His first look at the workshop convinced Johnson that habitability had been given no thought at all. In the course of their work, he and his colleagues had built up a store of information on design factors for all kinds of crew activity under circumstances of confinement and isolation; but their data might as well not have existed. Marshall, lacking experience in manned spacecraft, apparently had taken ideas from any available source—including the astronauts, whose talents as spacecraft designers, Johnson felt, were limited at best. But since Huntsville's engineers regarded crew quarters as part of their design responsibility, they were annoyed when Loewy/Snaith and Caldwell Johnson undertook to set them straight. Johnson understood their annoyance, but went ahead with his suggestions in spite of it.[18]

It took the rest of 1968 for Johnson to establish the boundaries of his habitability experiment and to define its content. The following May he summarized his approach.[19] Habitability, he said, was not an experiment in the usual sense; it was simply not practical to test several different design concepts. Instead, MSC's best design judgment would go into the workshop, and the missions would evaluate that judgment. Johnson took his task to be the creation of an operational system that would reduce the chores of daily living to a level "entirely incidental" to spaceflight operations. He proposed to deal with nine major components of habitability: environment, architecture, mobility and restraint, food and water, clothing, personal hygiene, housekeeping, communication within the spacecraft, and off-duty activity. By systematizing the man-spacecraft relationship, Johnson hoped to bring some engineering rigor into an otherwise chaotic field.[20]

HABITABILITY OF THE DRY WORKSHOP

The limitations of the wet workshop cramped the habitability experiment, as they did almost everything else, and after the wet-to-dry change it seemed that much more could be done; but Marshall showed no inclination to improve the workshop. A month after the change, MSC criticized the layout as "too austere"; far from providing the best that current technology could offer, "the present concept [looks like] a canvas tent city." The floor plan made no sense; the food management compartment was too small and the sleeping compartments too large. Later the same month, preparing for the preliminary design review of Marshall's habitability support system,* MSC found the workshop still "designed to the threshold of acceptability. . . . The dry workshop has none of [Apollo's] constraints, and yet an . . . austere design persists." Huntsville, however, had no plans to make substantial changes. Belew envisioned "only minor impact [on habitability] as a result of the 'dry' workshop configuration," and intended to use most of the wet-workshop hardware in the dry workshop.[21]

Early that fall it became obvious that there were at least two schools of thought on habitability. In Mueller's view, the workshop should be a laboratory to test concepts and devices, with a view to establishing criteria for design of future space stations. Both he and Schneider put habitability high on the list of Skylab priorities. Houston did not believe this laboratory concept was practical, but agreed with the importance Headquarters attached to improved habitability. The beneficiaries of this concern—the astronauts—cared less about styling and appearance than efficiency; they wanted a spacecraft in which they could do their jobs without a lot of petty annoyances. They were, in fact, somewhat disdainful of the attention given to such amenities as interior color schemes.† Since the astronauts were reviewing crew quarters concepts before anyone else at MSC was deeply involved, their advice was often (too often, some thought) followed at Marshall. Partly this was because Marshall engineers were a bit overawed by personal contact with astronauts; partly it was because the engineers hoped the astronauts would influence MSC's Skylab program office to accept Huntsville's decisions. Marshall was reluctant to make any but clearly necessary changes—which did not yet include habitability improvements.[22]

By September 1969 George Mueller was concerned that Huntsville was not acting on Loewy/Snaith's ideas, so he called a meeting on habitability for mid-October. Schneider spelled out the issues for the program offices on 30 September, noting that provisions for crew comfort left much to be desired. He did not intend to abrogate the minimum-change philosophy established in July, but "significant and necessary improvements [can be made] with relatively little cost or schedule impact."

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* The habitability support system included all of the hardware required to carry out the habitability experiment: lights, fans, floor and walls, food storage and preparation equipment, water supply, and so on.

† An astronaut-office joke recalled an early suggestion that the interior of the Apollo command module should be painted blue above and brown below, so that pilots disoriented by zero g would have an up/down visual reference. Michael Collins tells the story in *Carrying the Fire;* it was repeated to the present authors by some of the Skylab crewmen, with the implication that this was typical of the absurd things some people will worry about if they are encouraged.

Crew comfort was not the only consideration. Marshall should keep in mind that "a public image will be formed by TV transmissions" from the workshop in orbit. The recommendations of both Raymond Loewy and Caldwell Johnson were to be given full consideration; ways could be found to keep costs down and still improve the workshop.[23] Schneider had a way of emphasizing by understatement, and this memo indicated that Headquarters was more than a little impatient with the treatment habitability was getting.

The workshop principals (including Raymond Loewy, who came at Mueller's invitation) met in Washington on 14 October for a general review of the habitability support system. Mueller left the clear impression that he was not satisfied with the handling of crew quarters, remarking more than once that habitability was the most critical factor in future manned spaceflight—an attitude heartening to the MSC delegation, whose presentations focused on the shortcomings of current design in many areas.[24] During the day all aspects of habitability were discussed, including some that had major impact on the workshop structure. Both Loewy and Johnson had suggested rearranging the floor plan to provide a wardroom; both had also endorsed adding a large window to allow the crew to enjoy the view from orbit, something that had been impossible in the wet workshop. The wardroom was easily agreed to, but the window created an impasse. While everyone agreed that it would be very nice to have, Belew pointed out that a window posed one of the toughest problems a spacecraft designer could face. It was too costly, it would weaken the structure, it would take too long to develop and test, and it was not essential to mission success. Counterarguments could not rebut his position. Finally, Mueller asked Loewy for an opinion. The response was unequivocal; it was unthinkable, Loewy said, *not* to have a window. Its recreational value alone would be worth its cost on a long mission. With that, Mueller turned to Belew and said, "Put in the window." Schneider formally authorized the window and the wardroom, along with several other changes,* on 31 October.[25]

Not many habitability questions had to be settled at the associate administrator's level, but most of them did involve a great deal of two- and three-sided argument—usually Caldwell Johnson on one side and Marshall engineers on another, with the crews sometimes on a third. Seemingly minor details often produced disagreement. Johnson had to persuade the crews that the test pilot's traditional one-piece flight coveralls were not suited to long-term living in the workshop. In this they acquiesced, but they would not give up the pockets on the lower trouser leg—

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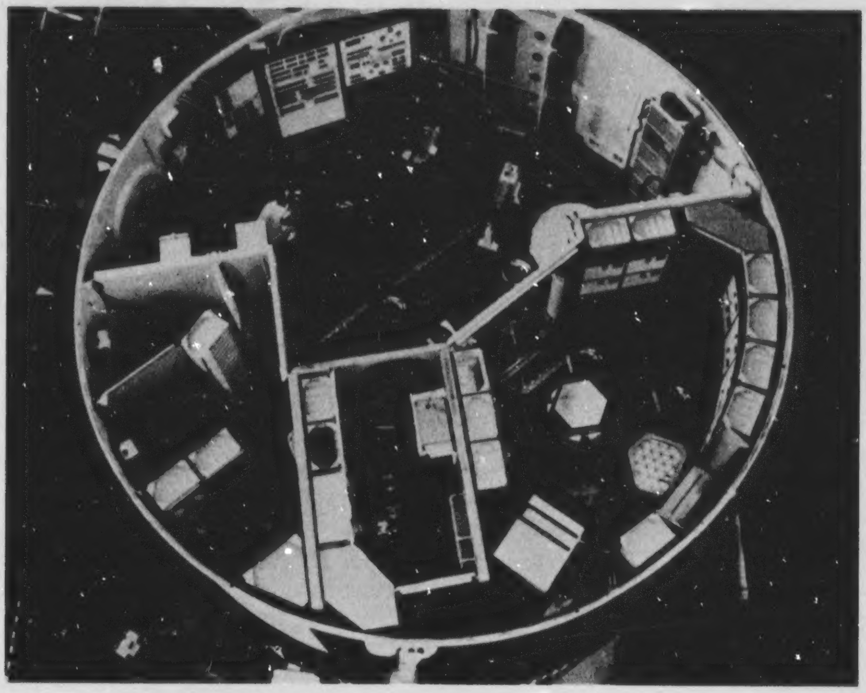
* One of these was a door cut into the S-IVB wall to provide access to the cluster during checkout at KSC. Besides making checkout easier, the door speeded up assembly of the workshop at McDonnell Douglas. W. K. Simmons, Jr., "Saturn I Workshop Weekly Notes," 1 Aug. 1969; R. M. Machell to mgr., AAP Off., "Weekly Activity Report," 29 Aug. 1969.



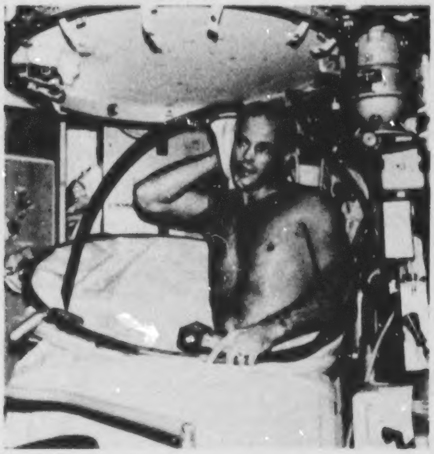
Lower deck (aft compartment) of the workshop trainer, with crew quarters in the foreground. Note the lack of chairs around the hexagonal galley table—chairs are pointless in zero gravity. Astronauts would sleep strapped to the walls of the cubicles at left, saving more floor space. The bathroom is in the center. Several experiments would be conducted in the work area at the top. Against the far wall is the lower-body negative-pressure device used in M092. In the center of the floor, partially hidden by a partition, is the hatch into the liquid-oxygen tank, which on Skylab *served as an oversize trash receptacle.* 72-H-87.

ideal for a pilot strapped into an airplane cockpit, but (Johnson believed) a useless impediment to moving around freely in zero g. Johnson and Fred Toerge designed a basic two-piece uniform to which a matching jacket could be added. It was both practical and attractive; Johnson had one of his staff wear a prototype to conduct a briefing in May 1969, and it "brought down the house," as he told Toerge later. Subsequent versions retained the three-piece design, but Johnson was disappointed when the crews spoiled the effect by covering the shirt and jacket with name tags and badges.[26]

When it came to matters of purely personal preference, such as off-duty relaxation and entertainment, Johnson was content to let crewmen have their choice. He proposed an entertainment center in the wardroom, equipped to show movies or provide music, but it drew no enthusiastic response. Nor did card or board games; crew preferences tended strongly toward reading and recorded music—provided everyone could have his own private tape player; musical tastes were quite disparate. As it turned out, this was about as much entertainment as anyone wanted, or had time for. Amusing themselves in off hours was no problem for any of the crews.[27]

Keeping clean was of more concern. Though Houston's medical experts were satisfied that sponge baths were enough to keep down serious dermatological problems, Mueller and Schneider wanted to provide some way to take a shower. In April 1969 Schneider told Belew to look into a lightweight, low-cost "whole-body bather" of some kind—not something on which the mission would depend, but which would permit the concept to be evaluated. Caldwell Johnson, although he thought it was not a good idea, provided a design concept and Belew dutifully sent it to McDonnell Douglas for a cost estimate. The contractor returned an estimate of over $3 million for a space bath and water reprocessor. Belew asked for and got permission to reject this proposal, but Schneider continued to press for an experimental device that could be tried a few times on the first mission. In the event, a simple shower went into the workshop and was used on all three flights, but it got mixed reviews from the crews.[28]

Many aspects of habitability were troublesome because there were no clear analogies for the workshop missions and little experience to draw on. Submarines seemed to be reasonably close parallels, but when astronaut Paul Weitz talked with knowledgeable Navy people early in the program, he learned little. Apart from some figures for optimum light levels and maximum noise limits, what the Navy had was mostly "anecdotal data"—sea stories. In 1969, however, when Grumman sponsored an oceanographic mission by the Swiss scientist and engineer Jacques Piccard, Marshall participated, hoping to gain some basic knowledge of habitability. Piccard's voyage, called the Gulf Stream Drift Mission, used a six-man submarine named *Ben Franklin*. It set out from Florida



Astronaut Jack Lousma, pilot on the second crew, in the shower. When the curtain was attached to the ceiling, the flexible hose with a push-button shower head could be used. Water was then drawn off by a vacuum system. The old-fashioned washcloth continued to work well under exotic conditions. SL3-108-1295.

on 16 July 1969 with a Marshall engineer in the crew, and 31 days later, having drifted 2700 kilometers submerged in the Gulf Stream, surfaced off Nova Scotia.[29]

Piccard visited MSC on 25 February 1970, and Caldwell Johnson took particular note of every complaint he made about living conditions aboard *Ben Franklin*. Reporting these comments to the Skylab office, Johnson passed along Piccard's statement that many of the faults had been pointed out before the mission, but Grumman engineers seemed unable to remedy them—or even to understand the complaints. Having had little success getting his own ideas into practice in 1969 and reflecting on *Franklin*'s similarity to *Skylab*, Johnson told the MSC Skylab manager, "if I hadn't known better, I would have thought I was listening to a debriefing of the first Workshop mission in 1973."[30]

THE FOOD SYSTEM

Nothing gave the workshop developers more trouble than the human digestive tract—and the experimenters whose main concerns were with what went into it and what came out of it. Food management and waste management would have been complicated enough as independent systems, but the imposition of stringent medical requirements made things much worse. The waste management system (see chap. 8) produced major design problems down to a few months before launch; the food system was brought under control by the end of 1971.

Contemplating two-month missions, almost everyone agreed that space food had to be improved. In Mercury and Gemini, crews had not complained about food, even though it was designed to meet the engineering requirements of spaceflight rather than to appeal to the palate. Compressed, processed, and packaged, space food was an engineering triumph: it took up little space, it would survive launch without disintegrating, and it would last almost indefinitely. Furthermore, it provided balanced nutrition to sustain life up to 90 days—provided, as one official put it, a way could be found "to influence the crews to eat [it]."[31]

The first three manned Apollo flights in 1968 and 1969 brought complaints about the food. This was somewhat surprising, because the food was much the same as in Gemini, and some of the same astronauts had found it quite acceptable. Seeking an outside opinion, MSC nutritionists persuaded Donald D. Arabian, chief of MSC's Test Division, to evaluate Apollo rations. Although he admitted to being "something of a human garbage can," Arabian found the experience one he did not care to repeat. He had agreed to subsist on Apollo food for four days, but the prospect quickly became unappealing. The sausage patties in his first breakfast resembled "coarse granulated rubber with a sausage flavor," which left a sickening aftertaste that persisted for an hour. At the end of the first day Arabian noted a marked loss of appetite; by the third day, eating was a real chore. Meal preparation offered no pleasant anticipation; there were no aromas to stimulate the appetite and no textural variety to provide satisfaction. Those items that most closely resembled off-the-shelf foods were excellent, but those prepared especially for spaceflight could only be called bad. Arabian could not understand why such common items as peanuts and chocolate had to be ground up and converted into bite-size cubes, which stuck to the teeth.[32]

Improving the food and solving the problems of long-term storage would have been challenge enough to food-system developers; superimposed on those were the rigorous requirements of the medical experiments. From the earliest days of AAP, medical scientists had planned to conduct a mineral balance study, measuring the astronauts' intake and output of calcium and nitrogen as part of the effort to understand the effects of long periods of weightlessness on man. Gemini had shown that astronauts lost calcium from bones and nitrogen from muscle—not enough to be operationally dangerous on a lunar landing mission but potentially serious for longer flights. Nothing was done in Apollo, however, and in 1969 the medics knew no more about the process than in 1966. Two Skylab experiments, M071 and M073, were designed to determine how long the losses continued, how serious they were, and whether anything could be done to arrest or reverse the changes.

Experiment M073 measured the urinary output of several substances of metabolic importance; its requirements affected mainly the urine and feces collection systems. M071, on the other hand, required accurate control of mineral intake as well as accurate measurement of output. Mineral-balance studies are common but exacting procedures. The subjects, usually hospital patients confined to bed, are given a constant, carefully measured supply of the constituents under study (calcium and nitrogen), and their total output of urine and feces is collected, accurately measured, and carefully analyzed. Even in a well equipped hospital such studies are difficult; on *Skylab*, experimenters proposed to conduct them on active astronauts engaged in a host of other activities at the same time.[33]

For medical purposes the best diet was made up of homogeneous items whose composition could be accurately determined and controlled—pureed vegetables, puddings, and compressed, bite-size solids. Dehydrated foods were acceptable, provided they were reasonably uniform, but heterogeneous items like spaghetti and meat balls or turkey with gravy posed serious problems for the experimenters. The diet that best suited the scientists, however, was the very kind that could be depended on to provoke strong crew resistance. For missions of four to eight weeks, management at Houston believed the crews should be pampered, and good food was one way to make long missions tolerable—or perhaps more accurately, bad food was a sure way to make them intolerable. Mueller, Schneider, and Caldwell Johnson, probably reflecting the complaints passed on by the Apollo crews, began to campaign for more conventional and appealing meals that could be eaten in more or less normal fashion, rather than pastes to be squeezed from tubes or cubes to be eaten cold. It could be done; the *Apollo 8* crew had enjoyed a hot meal of turkey and gravy, eaten with a spoon, and the effect on morale was remarkable. Johnson recognized a challenge in designing a food system that would remove many of the engineering restrictions that had limited space menus, and in the spring of 1969 he began formulating some ideas.[34]

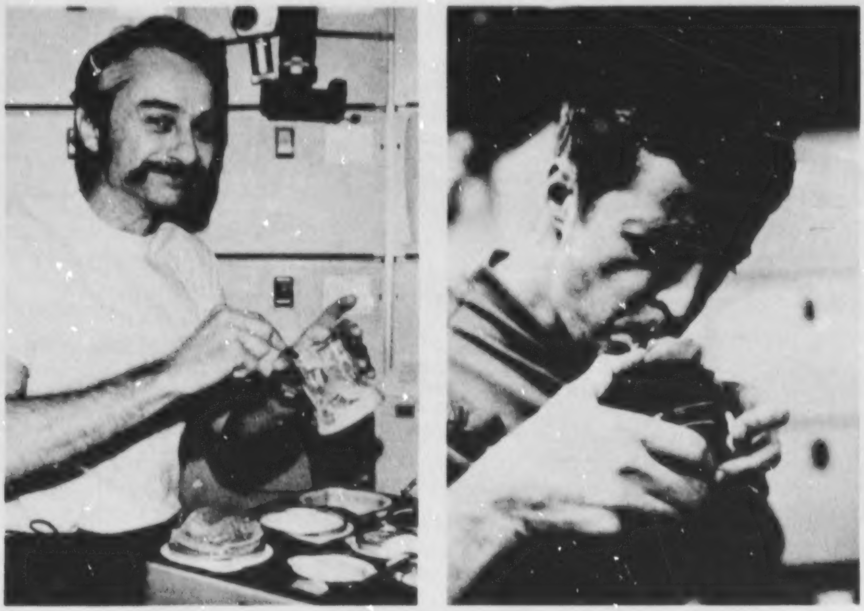
By the time the dry workshop was baselined, the food system was not defined in detail, though its major constraints were understood. In April 1969, Paul C. Rambaut noted that medical requirements and habitability considerations sometimes conflicted. The latter, however, took precedence; if the experiments made the food intolerable, the experiments would have to yield. Rambaut, an MSC nutritionist who was principal coordinating scientist for the M070 series of experiments, expected Skylab to use a wider variety of foods, including hot and cold items; and the workshop's food management compartment would provide some of the amenities of conventional dining.[35]

At the April Management Council meeting, not long after the *Apollo 9* mission and its crew's complaints about the food, George Mueller decided something should be done about it. On 22 April, Schneider offered some guidelines to the MSC program office. It was time to get away from complete reliance on Apollo-type food, he said, and provide something more like normal cuisine—perhaps frozen dinners, freeze-dried camping foods, possibly even fresh fruits and vegetables. He recognized that providing for stowage and preservation would affect workshop development, but suggested that if meals could be greatly improved, the weight and volume allowances for food could be raised by as much as 10%.[36]

Marshall had already held a preliminary requirements review in late March; at that time MSC's specifications had been rather broad: an estimate of total storage space, plus provision for heating and cooling certain items during preparation. On 16 April Johnson urged the Houston program office to add a food freezer; a Martin Marietta study had convinced him it was feasible, and it would permit a much greater variety of food to be taken along. In May, MSC's program office sent Huntsville a new set of requirements, including a freezer, an oven, and provision for protecting stored food from pressure changes. The new specifications called for five classes of food: dehydrated, intermediate moisture, wet-pack (heat-sterilized items similar to the turkey dinner provided on *Apollo 8*), frozen, and perishable fresh foods. Marshall was uneasy about the escalation in size and complexity of the larder and galley at this late date, but went along, since Headquarters urged the improvements. By the end of July, after several meetings involving both centers and McDonnell Douglas, the new requirements had been accepted and several concepts were under study.[37]

Houston was late with its definition of the food system for several reasons. During the wet-workshop phase of AAP, dieticians at MSC had depended on data from the Air Force Manned Orbiting Laboratory, expecting to modify systems and procedures to meet Skylab's medical requirements. When MOL was canceled in June 1969, full responsibility suddenly fell on the MSC group, already overloaded with Apollo duties. With Marshall clamoring for storage and preparation requirements, Caldwell Johnson designing a completely new system, and the development contract not yet firm, MSC's chief of food and nutrition pleaded for help. He wanted three more persons assigned to food-system integration at Martin Marietta. The request for proposals on the food system had to be out in two weeks, and Martin Marietta should be working on

Astronaut Owen Garriott, scientist-pilot on the second crew, at dinner, left. SL3-111-1519. *The tray contained heating elements for preparing the individual packets. Right, Astronaut Joseph Kerwin, scientist-pilot on the first crew, trying a grape drink in the workshop trainer. Beverage powder was packed in collapsed accordion-shaped containers that expanded in length as water was added. Crushing the container expelled the contents.* 73-H-275.



eight other problem areas as soon as possible. It took another five months to get food-system management in hand.[38]

Marshall's uneasiness about the changing requirements turned into alarm in mid-1969, as it became clear that Houston was just beginning to work over the food system. That fall, Caldwell Johnson proposed to simplify the development of the food system by taking the engineering problems off Marshall's hands. Another contractor should take charge of storage and preparation equipment, furnishing to the workshop contractor a complete system, ready to be installed. Backing up this proposal, he submitted a concept for a simplified storage and preparation system, packing individual servings of food in metal containers shaped to fit compactly within a pressure-proof canister. One protective canister held several days' supply of food, so the wardroom pantry could be replenished once a week. The food containers were designed to fit the compartments in a preparation and serving tray, where they could be heated as required. To prepare a meal, the crewman who had chef's duties would simply take out the items on the menu, add water to dehydrated foods, secure the containers in the tray, turn on the automatically timed heating elements, and let the tray do the rest. After the meal the containers could easily be weighed to account for leftover food (as required by the medical experiments) and then discarded, with very little mess.[39] This proposal was not adopted in its entirety, but several of the basic concepts found their way into the final food system.

MARSHALL CALLS FOR A REASSESSMENT

Lee Belew, Skylab program manager at Marshall, expressed reservations in July 1969 about his center's ability to meet a July 1972 launch date. By the fall of 1969, when Headquarters agreed that several major jobs should be farmed out to contractors, he felt he could make it—provided everyone followed the minimum-change directive that both Schneider and Mueller had affirmed. Instead, both Houston and Washington spent the rest of the year thinking up improvements—mostly in habitability—that cost time and money. In November Belew remonstrated to Schneider that changes were threatening his budget and schedule. The tradeoff studies that had to be done on proposed improvements siphoned off Marshall's manpower and delayed action. Either costs would go up or the schedule would slip unless Marshall got some relief.[40]

From Caldwell Johnson's point of view, nothing much was happening; so few of his suggestions were being acted on that by early 1970 he felt compelled to go outside normal channels to make his points. He got a chance the first week in April, when center directors, program managers, and key technical people set out on a four-day tour of Skylab contractors' plants for a first-hand assessment of the program's condition. At every stop Johnson called Gilruth's attention to the sad state of habitability features, losing no opportunity, as he recalled later, "to put the needle in." Many of the faults he pointed out were minor, and some were only apparent because the mockups were not accurate, but the effect was what he intended. Habitability became an issue.[41]

Chris Kraft, MSC's deputy director, put the matter with characteristic bluntness as soon as the tour was over. "I think," he told his chief, "that everyone who has a feel for the problems of living in space came away from the Skylab tour with the same thought—that insufficient attention has been paid to how the astronauts are going to live during those very tedious missions." No matter that the contractors had all protested that the crews had reviewed their work; Kraft said the astronauts should not have the last word anyway. "They are too prone to accept a make-shift situation on the basis of 'that's the way things have been done in the past.'" He suggested that Gilruth assign perhaps 10 people to review habitability and assure that proper attention be given to it.[42]

Gilruth sent Kraft's memo to Eberhard Rees, urging Houston's concern on Marshall's new director.* Passing the letter along to Belew, Rees remarked that Kraft's points were well taken. Rees had spent enough time at an Antarctic base early in 1967 to appreciate some of the hardships of a less-than-ideal environment, and he felt that MSC's suggestions ought to be examined, "even if [implementing them] costs more money." He wanted Belew to appoint someone to examine the whole matter without considering cost. In response, Belew sketched out the history of the habitability problem, listing several major accommodations Marshall had already made. Evidently he brought the director around to the Skylab office's view of the matter, for Rees's answer to Gilruth emphasized Marshall's concern for costs and schedules. Habitability changes, Rees said, were on the point of changing the whole Skylab program concept. It was time either to reaffirm Skylab's fund-limited and experimental nature or to commit the program to a different objective.[43]

Others at Huntsville had just about reached the end of their tethers on habitability matters. The chief of the Man/Systems Integration Branch reacted impatiently to Caldwell Johnson's comments on the *Ben Franklin* mission. The source of the "hardships" that *Franklin*'s crew had endured was no mystery; it was lack of money. Tradeoffs had been made with full consideration of habitability provisions, and the little submarine had proved adequate to perform a successful mission. Skylab's habitability changes (most of which were trivial) were about to "send the program into convulsions." Certain amenities had to be provided, but unless program officials were careful they might be doing nothing more than "a job of interior decorating."[44]

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* Von Braun had been promoted to Deputy Associate Administrator for Planning 13 Mar. 1970. Rees was born in Württemberg, Germany, in 1908; he received an M.S. in mechanical engineering from Dresden Institute of Technology in 1934. During World War II he was technical plant manager at Peenemünde. He came to the U.S. with von Braun in 1945, working first at Fort Bliss and later at the Redstone Arsenal. He became a deputy director of Marshall in 1960.

Belew had asked Gaylord Huffman, technical assistant to Marshall's workshop project manager, to survey the habitability question. Huffman reported his recommendations in June. He concluded that the purpose of the experiment should be changed; NASA could learn more by testing a variety of concepts. He also felt it would be best to move the principal investigator's responsibility to Huntsville. Current attempts to satisfy the crew and the principal investigator, who frequently disagreed, were the main reasons for the almost continual redesign of workshop systems. That problem, he implied, was best solved by getting a new principal investigator. Besides, the *Ben Franklin* mission, in which Marshall had participated, was a better analogy to *Skylab* than an Apollo mission—which, after all, was the only experience Houston had.[45]

After the tour of contractor facilities, Gilruth, wanting to be sure that Caldwell Johnson's criticisms had some foundation, appointed an ad hoc committee to examine them. Late in May the committee submitted 17 pages of detailed recommendations for correcting the deficiencies Johnson had been citing for months. Attached were 15 requests for engineering design changes, approved by MSC's Skylab office and classified as "mandatory for operational suitability." Gilruth forwarded the report and the change requests to Rees on 26 May 1970, characterizing them as "requirements." Acknowledging that Houston had acquiesced in Marshall's workshop design—probably longer than it should have—he nonetheless felt strongly that crew comfort had to be assured on missions as long as those proposed for *Skylab*. MSC's management had not approved all of the committee's findings, but those forwarded to Marshall were considered necessary.[46]

Rees's reply reflected surprise and dismay, the more so because the new requirements were produced by people who had been working with Marshall for more than three years. Without disputing that many of Houston's demands were desirable, Rees was alarmed at their cumulative effect—an assessment much like Gilruth's criticisms of the wet workshop at the "warning flags" review of November 1967. As Rees saw it, the Skylab program was in danger of running off in all directions unless Headquarters and the field centers were working to the same rules, and he had so advised Headquarters.[47]

One of the 15 mandatory changes was the new food system that Johnson and MSC's nutritionists had just got down on paper. Selling it to the Marshall program office was not easy, since the MSC proposals involved thoroughgoing changes to a design that McDonnell Douglas had already started to fabricate. May and June saw a series of meetings between the center program offices and the contractor, with MSC doggedly insisting on change and Marshall tenaciously arguing that the cost and schedule impacts would wreck the program. Houston not only proposed a drastic increase in food storage space, but also lower freezer temperatures, a relocated wardroom table, and a new food tray requiring a special fixture in the galley. Coming as they did on top of serious problems that were developing in the urine collection system (chap. 8), MSC's proposals were just about the last straw for Marshall's Skylab office—and it looked as though Houston was not finished with the new design.[48]

Responding to Rees's pleas, OMSF chief Dale Myers scheduled a top-to-bottom program review for 7–8 July 1970 at Huntsville. Marshall's major worry was with fundamental program guidelines. Was Skylab an experimental, fund-limited program, or was it supposed to be the next Apollo? Houston, on the other hand, came to the meeting with yet another series of proposals requiring more changes. The medical experimenters, concerned about the humidity and carbon dioxide levels in the workshop, wanted the environmental control system changed. The major question raised about habitability was the high cost of MSC's new food system; but since no one could suggest a cheaper alternative, it came through practically untouched. Schneider was not sure that the new arrangement would simplify management and reduce costs, as Houston argued, but after detailed examination of the tradeoffs, he agreed to it. Headquarters representatives, pointing out that habitability factors were uncommonly difficult to reduce to numbers, pleaded with both field centers to make more effort to negotiate their differences, Marshall making more allowance for intangibles and Houston showing more cost consciousness.[49]

The program review approved significant changes while reaffirming both the July 1972 launch date and the existing cost ceilings. Rees conveyed his disappointment to Charles Mathews later in the month. The review had made Marshall's task nearly impossible; the approved changes took absolutely all the slack out of his center's schedule. Furthermore, he expected still more changes to come; everyone but Marshall seemed eager to upgrade Skylab far beyond its origins as an austere, experimental program. If that trend continued, NASA's ability to get on with other programs would suffer, because it would appear that Skylab's cost had been seriously underestimated. Rees then summarized his center's view of the past year's events:

> We started with an open-ended astronomy mission where we were ready to take a number of risks . . . and where habitability accommodations were consistent with an early launch/lower cost approach. . . . we are proceeding to perform in orbit a very sophisticated and unprecedented medical experiment where the subjects must be handled delicately so as not to disturb the medical baseline.

The trouble was that the desirable changes often had serious impact on other systems—the medical experiments being horrible examples—and Rees wondered where it would all end. Marshall would go along with the decisions reached at the review, but Rees did not believe that the schedule could be met within the budget.[50]

Mathews's response indicated his sympathy with Rees's problems, but he again stipulated that the July 1972 launch would be met—and within budget. Some compromises would no doubt have to be made in order to reconcile resources with requirements; but the basic Skylab philosophy, "economical application of existing hardware with minimum new developments . . . consistent with basic objectives," still held. As for the exceptions made in the past year, each had powerful justification, and their approval did not signal departure from the policy. He reminded Rees that "Skylab may be the only manned mission flown for an uncomfortable number of years [and] it is critical that we make the most of this opportunity." It would take the best management that NASA could muster, but Mathews was confident that Schneider and the center program managers could do it.[51]

In mid-August Rees wrote to Gilruth summarizing the status of MSC's engineering change requirements of 26 May. After a good deal of horse-trading, in which MSC withdrew some requests and others were disapproved because of excessive cost or delay, the major changes in the food system had been adopted. Rees urged his MSC counterpart to help him hold the line against further changes, because Marshall had neither the funds nor the time to accommodate them.[52]

In fact, the workshop suffered no more spasms from habitability requirements. The next big headache came from the waste collection and measurement systems (chap. 8). Later in 1970 the astronauts would raise some issues with the medical experimenters about the food, but the impact on the major food systems was unimportant. Caldwell Johnson's office kept an eye on the development of habitability systems, while he turned his attention to design problems in Shuttle and in the embryonic Apollo-Soyuz Test Project.

8

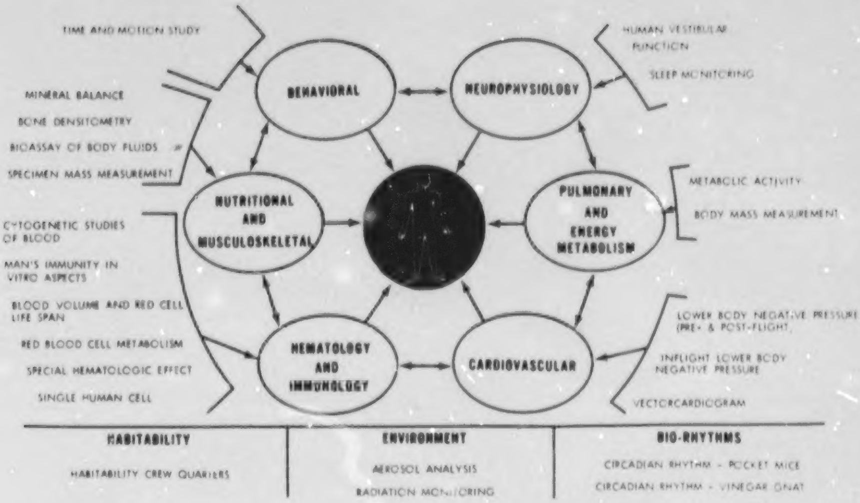
The Medical Experiments

Medical experiments were one of the major justifications for the workshop from the outset, and Houston's medical researchers knew what they needed to investigate. The experiments defined in late 1966 sought answers to questions raised by experience in Mercury and Gemini: What changes does weightlessness produce in the human body? How long do the changes go on? How does man adapt, if he does; and what can be done to counteract the changes if he does not?

Responsibility for developing the instruments to conduct these experiments lay with the Manned Spacecraft Center's Medical Research and Operations Directorate. Normally the physicians would have laid down the experiment requirements, while the Crew Systems Division and the Engineering and Development Directorate designed and built the hardware. But shortly after the medical program for Skylab was approved, the Apollo spacecraft fire threw all of Houston's arrangements askew. As one result, the medical experiments did not get coordinated attention from all Manned Spacecraft Center offices until 1969. Their development was plagued by technical problems—not unexpected, considering their complexity and novelty—that often threatened to delay Skylab's launch. Through a sometimes stormy four years, MSC and Marshall worked hard on these experiments; but the work paid off, for all of them functioned without major failure through all three manned missions.

DEFINING THE EXPERIMENTS

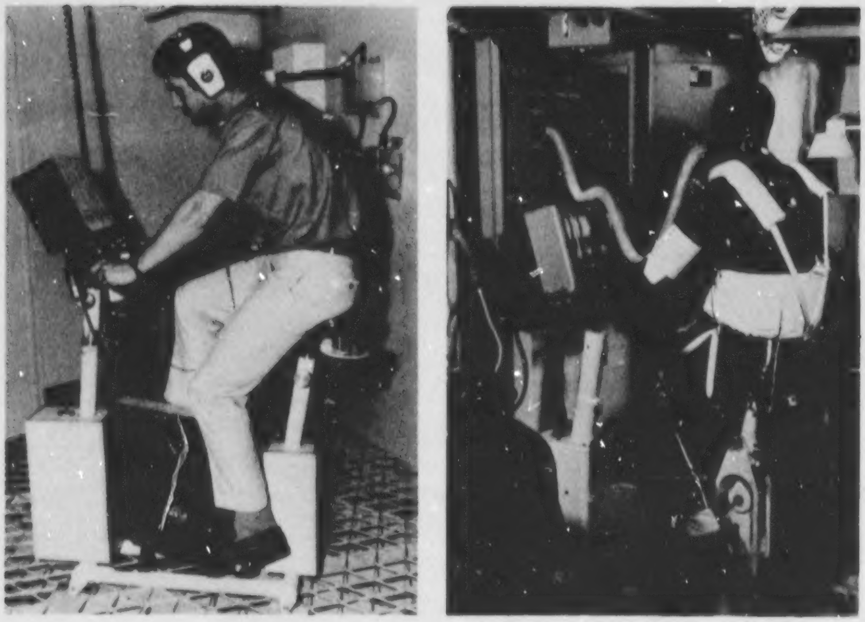
Among the first experiments submitted for AAP missions were three medical studies: metabolic activities, cardiovascular function assessment, and bone and muscle changes. The first grew directly out of the unexpected difficulties the Gemini astronauts had with extravehicular activity and was designed to determine whether physical work was more demanding in zero g than on the ground. This experiment used a bicycle


TIME AND MOTION STUDY
MINERAL BALANCE
BONE DENSITOMETRY
BIOASSAY OF BODY FLUIDS
SPECIMEN MASS MEASUREMENT
CYTOGENETIC STUDIES OF BLOOD
MAN'S IMMUNITY IN VITRO ASPECTS
BLOOD VOLUME AND RED CELL LIFE SPAN
RED BLOOD CELL METABOLISM
SPECIAL HEMATOLOGIC EFFECT
SINGLE HUMAN CELL
BEHAVIORAL
NEUROPHYSIOLOGY
NUTRITIONAL AND MUSCULOSKELETAL
PULMONARY AND ENERGY METABOLISM
HEMATOLOGY AND IMMUNOLOGY
CARDIOVASCULAR
HUMAN VESTIBULAR FUNCTION
SLEEP MONITORING
METABOLIC ACTIVITY
BODY MASS MEASUREMENT
LOWER BODY NEGATIVE PRESSURE (PRE- & POST-FLIGHT)
INFLIGHT LOWER BODY NEGATIVE PRESSURE
VECTORCARDIOGRAM
HABITABILITY
HABITABILITY CREW QUARTERS
ENVIRONMENT
AEROSOL ANALYSIS
RADIATION MONITORING
BIO-RHYTHMS
CIRCADIAN RHYTHM - POCKET MICE
CIRCADIAN RHYTHM - VINEGAR GNAT

The medical experiments and their interrelationships, a briefing chart used at NASA Headquarters in 1971. ML71-5271.

ergometer, a highly instrumented version of an exercise bicycle, to measure the rate of energy expenditure during controlled exercise. The ergometer was to be used frequently during the missions so that trends with time could be detected, if they existed. The second study, cardiovascular function, assessed changes in the heart and circulatory system resulting from the absence of gravity. This required stressing the heart (which has less work to do in weightlessness and grows lazy) by subjecting the astronaut's lower body to a partial vacuum, simulating the effect of gravity in drawing blood into the legs. Changes in blood pressure, heart rate, and leg volume were telemetered to the ground, where physicians assessed the condition of the subject's heart and blood vessels. Supporting the medical experiments was a sophisticated system that supplied power, provided gases for the metabolic experiment and vacuum for the lower-body negative-pressure device, displayed certain critical data for the astronauts on board, and transmitted information from the experiment sensors to the ground.[1] The third major experiment, bone and muscle changes, was the mineral-balance experiment described in chapter 7. At Headquarters and at MSC, aerospace medical experts spent much of 1967 defining the experiments in detail and selecting principal investigators for them. Not until November 1967 was the program organized, fully defined, and submitted to the Manned Space Flight Experiments Board for review.[2]

Engineering assistance was hard to come by at Houston in 1967 in the aftermath of the Apollo fire. Everything was subordinated to getting Apollo into shape and recovering time lost in the lunar landing schedule.



Two developmental versions of the ergometer at Marshall Space Flight Center, June (left, 0-08627) *and September 1970 (right,* 011738).

In these circumstances Dr. Charles A. Berry, director of Medical Research and Operations, was hard pressed to get the medical equipment built on time with the funds available. At a meeting of program officials at Kennedy Space Center in March 1968, Wernher von Braun suggested to Berry that Marshall could fabricate some of the equipment, saving time and money. Although von Braun carried away the impression that Berry welcomed such assistance, follow-up contacts indicated considerable reluctance. When von Braun formally proposed the arrangement, Gilruth's reply was polite and almost noncommittal. Berry had advised his chief that he was not convinced Marshall could meet MSC's requirements.[3]

Since everyone agreed that these experiments could easily become a pacing item for the program, Marshall wanted to help if possible. Talks continued into the fall, Marshall trying to get a commitment and MSC demanding detailed information as to how Marshall would conduct the project. On 30 October 1968 the centers agreed that Marshall would build the ergometer (and the gas analyzer that went with it), the lower-body negative-pressure device, and the experiment support system. The dollar value of the project was not large (an estimated $4 million), but the engineering challenge was substantial and would extend Marshall's expertise into a new area. A task team from the Propulsion & Vehicle Engineering Laboratory, headed by Robert J. Schwinghamer, was established and work got under way.[4] The arrangement looked simple, but it turned out otherwise. It was hard for one center to direct another as it would a contractor, and during the next few years relations were occasionally strained. But in the afterglow of a successful program, most participants agreed that the strains had produced a creative tension that resulted in first-class equipment.[5]

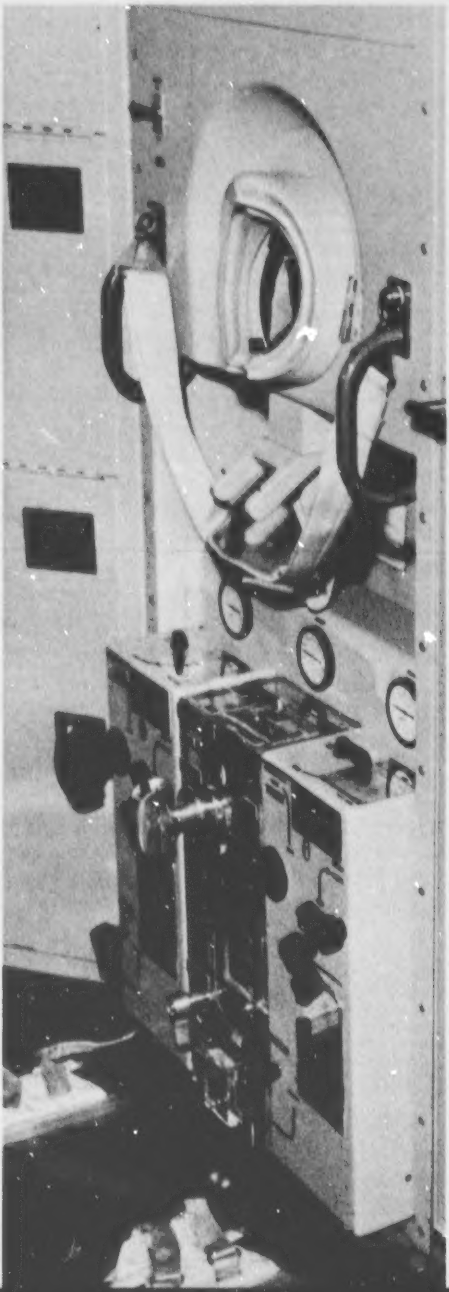
A SPACE TOILET

While one group at Marshall worked on medical experiments, another group was coming to grips with a more complex problem: providing a system for waste management in the workshop. The problem had new dimensions in Skylab. Previous programs had required no more than a sanitary method of collecting and disposing of body wastes with a minimum of handling; but for Skylab, the medical experiments required collection, measurement, and return of both urine and feces for analysis. Gemini and Apollo systems would not do, even if—as they were not—they had been ideal from the user's point of view.[6]

The design of a system to collect and measure urine was driven by two considerations: the requirements of the mineral balance experiment and the astronauts' insistence on a system that was easy to use and failure-proof. As the medical requirements stood in late 1968, each urine void had to be measured with an accuracy of 1%, a sample (10%) of each void had to be collected and dried, the solid residues being combined daily. The system had to prevent contamination of one crewman's urine by another's. Each day's samples were to be tagged with identifying data: who, when, and how much. At the end of a 28-day mission, a Skylab crew would have something like 540 grams of neatly packaged urine solids to bring back to the labs.[7]

The engineering problems involved in collecting liquid, separating it from air, measuring it, and accurately sampling it, all in zero g, were formidable. Only two systems were available: one that the Fairchild Hiller Corporation had devised for the Air Force's Manned Orbiting Laboratory and one that the General Electric Company had developed for the Biosatellite program, where the subject was a seven-kilogram monkey. While GE's prototype could measure volumes within 0.2%, Fairchild Hiller's was designed for only rough volume measurements. Marshall believed the Fairchild Hiller system would be easier to develop in the time available, but MSC's medics did not think it could meet their requirements for volume measurement and sampling. They were willing to wait for comparative test results, but wanted the GE system kept under consideration. In spite of Houston's warnings, Marshall took the advice of McDonnell Douglas, prime contractor for the MOL as well as the Skylab workshop, and decided to adopt the Fairchild Hiller system.[8]

By early 1969 the medical experimenters were reconsidering their requirements. In January word got back to Marshall that investigators wanted to collect all the urine for a 24-hour period, mix it, measure it, and take out a sample to be frozen. Pooling before sampling would reduce the chances for error in measurement; the change to freezing arose out of concern for the stability of some urine components. Organic compounds



The waste-management unit in June 1971. Having the toilet mounted in the middle of the wall posed no problem in zero gravity. Between the toilet and the lap belt is the holder for the urine receiver. Urine would be collected in the three drawers at the bottom. The foot restraints on the floor proved of little use. MSFC 020096.

(hormones and steroids) would be partially destroyed by the conditions of drying Marshall proposed to use (heating to 60° C under vacuum). Principal investigators feared their results would be challenged by other researchers unless the samples were preserved by a standard method, and freezing was the only accepted method.[9]

Since no freezer was planned for the workshop at that time, Marshall took strong exception to this costly and time-consuming change. Besides, Fairchild Hiller's medical consultants insisted that drying was perfectly adequate. MSC challenged this assertion vigorously at the preliminary requirements review for the habitability support system on 25 March 1969; Marshall proposed a study to prove the point, and MSC agreed. McDonnell Douglas was directed to compare drying with freezing to verify that vacuum drying would not alter the urine components—or if it did, to show that the changes were predictable. After MSC reviewed the contractor's test proposal, an independent analytical laboratory was picked to conduct the test. It was expensive and would take time, but Marshall engineers felt that if an independent study killed the requirement for a freezer, the time and money would be well spent.[10]

Houston was equally determined to establish freezing as the method for urine preservation. Early that summer, Bob Thompson emphasized to Belew that the only acceptable procedure was to chill the urine immediately after collection, sample it, and freeze the samples for return. When in July the centers agreed to provide for frozen food in the workshop, McDonnell Douglas was directed to resume preliminary design studies on a urine freezer. Paul Rambaut, MSC's principal coordinating scientist for the urine experiments and deeply involved in both the waste management and food systems, saw considerable irony in this turn of events. While the scientists concerned with urine constituents unanimously agreed that urine samples must be frozen, nutritionists equally agreed that frozen food was *not* required. Yet the food freezer was accepted with little resistance from the engineers, while the urine freezer was strenuously opposed.[11]

Throughout the summer, Houston's medical directorate was skeptical of Marshall's intentions, suspecting that the effort to provide a urine freezer was not being pursued seriously. They continued to warn their center's Skylab office that even if the study showed drying to be acceptable, it was still "open to suspicion because it is not the standard approach used by the authorities in these fields of investigation." As far as other aspects of the Fairchild Hiller system were concerned, the medical experimenters had no confidence in its method of volume determination, and they began to investigate an alternative technique using a chemical tracer.[12]

In late October 1969, Bill Schneider decided to try to resolve these questions. He called Headquarters and center program officials to

Huntsville on 21 November for a discussion of the issues. The test results on the two urine preservation methods were not yet available, but preliminary indications were that freezing was no better than drying. After examining the engineering tradeoffs, Schneider reaffirmed current plans, but allowed the freezer study to continue. Dismayed by this decision, MSC's medics asked for another review. In Houston on 18 December, Marshall reviewed the experiment requirements that MSC had established, pointing out that freezing was not specified. After reviewing the engineering considerations and test results, Marshall made its recommendations: stay with the present system (drying), stop all work on sampling and freezing, and go on with urine storage tests to establish the rate at which the heat-sensitive components were lost with time. Once more, Schneider saw no reason to change to freezing. All Houston could get was an agreement to have Fairchild Hiller's test results reviewed by an independent consultant and to study the impact of sampling and freezing on workshop systems. Directing Marshall to start this study, Schneider emphasized that if a change to freezing caused a schedule delay, Marshall was to find a way to work around the bottlenecks and keep the workshop on schedule. On 30 December Marshall ordered McDonnell Douglas to do the study.[13]

During the next three months, Fairchild Hiller and its subcontractor, Bionetics, Inc., of Bethesda, Maryland, completed the studies on drying versus freezing. MSC methodically pecked away at the results and statistical analysis. The test results seemed ambiguous. Fairchild Hiller's program manager admitted as much on submitting the final test report: "In effect the statistics are a draw." But MSC had run some tests of its own, which showed greater loss of hormones in dried samples than Bionetics had found. After the February meeting Paul Rambaut summarized the situation and recommended that the drying process be dropped once and for all. Severe and unpredictable deterioration of the heat-sensitive compounds *did* occur, and (once more) no recognized expert considered heat-drying to be acceptable for the proposed study. Acknowledging the engineering problems that Marshall faced in providing for freezing, Rambaut nonetheless saw nothing to be gained by further attempts to qualify the drying process for the Skylab missions.[14]

With the results in, Schneider convened one last meeting on 10 March to consider their implications. Though Huntsville stuck to its guns, it could not rebut Houston's arguments. (Marshall had not had time to do its own statistical analysis of the Bionetics results.) Houston's tactics and arguments finally prevailed, and Schneider ordered an immediate change in the urine processing system to provide for freezing the samples.[15]

In retrospect this was probably the most vigorously contested point in the entire workshop program. Stan McIntyre, Marshall's project engineer for the urine system, later summarized his center's view. "We knew that when we went into the complexities of pulling samples, handling fluids in zero g was going to be a complex gray area that nobody had ever been in." Rather than tackle that job they elected to avoid it, and their contractor's scientific adviser assured them that drying would satisfy the medical objectives. Berry, on the other hand, insisted that MSC knew all along that the Fairchild Hiller system would not work, and he so warned von Braun. What irritated Berry most, however, was the engineers' insistence on arguing with medical experts about what was essentially a medical question. In the end, though Marshall accepted the change, Skylab engineers were not convinced. The workshop project manager at Huntsville commented four years later, "to my dying day I'll always say we should have dried the urine instead of freezing it."[16]

With the freezing question settled, attention turned to volume measurement. The experimenters wanted the total daily urine output measured within 2%—a difficult goal, since liquids collected in zero g always entrap gas. Fairchild Hiller's system employed a synthetic membrane made up of microscopic fibers of liquid-repellent material, permeable to gases but not to liquids. A section of the urine collection bag was made of this material, and the company's engineers had designed the bag (so they assured McDonnell Douglas) so that surface tension would separate liquid from air. With the bag properly oriented, a squeezing device forced air out through the membrane while the urine was retained. The volume of liquid was measured by determining its thickness while the bag was confined in a box of fixed length and width. General Electric's system used a different principle; it separated air from urine with a centrifugal separator and used a peristaltic pump to measure volume and collect a proportional sample.[17]

In the spring of 1970 program officials began evaluating the two systems. McDonnell Douglas tried hard to sell the Fairchild Hiller system; Houston's medical team strongly backed the GE device, partly because they felt it offered better prospects for future development. Marshall's program officials might ordinarily have gone along with their prime contractor, but seemed skeptical of Fairchild Hiller's scheme; and they might have thought it prudent not to start another argument with Houston. At a review on 3 April, the GE system seemed to have clear technical advantages, but company representatives appeared reluctant to undertake development of the system for Skylab. McDonnell Douglas vigorously defended its subcontractor's system, asserting that it could "easily guarantee" an accuracy of 1% in volume measurement. MSC evidently could not persuade General Electric to compete, so in May the Fairchild Hiller system was selected for development and testing.[18]

When Fairchild Hiller's collection bag was tested in zero-g aircraft flights, however, it failed. The liquid-impermeable membrane did not function after prolonged contact with urine, and the bag would have to store urine for a full day during operations. For all the confidence the company had in its analysis of the forces acting on liquids, urine might nevertheless come in contact with the filter. The small unbalanced forces always present during zero-g aircraft maneuvers were enough to cast doubt on the whole concept. The company proposed a number of remedies, but all would take time.[19]

Center and contractor engineers spent a busy September trying to devise alternatives or to fix the system they had. Three major meetings during the month did nothing to raise confidence in it, and a proposal to use two bags, one for collection and another for measurement, created new problems. Headquarters, meanwhile, had learned that fluid-mechanics experts at Langley Research Center were working on gas-liquid separation in zero g using a centrifugal separator. Preliminary discussions between Langley and Marshall indicated that Langley's device was worth further examination.[20]

After reviews, meetings, and studies during October, Schneider, Belew, and Kleinknecht decided to continue working on three systems (the original one-bag design, a two-bag design, and the centrifugal separator) until one showed distinct advantages. Since the question of volume measurement was still in doubt, MSC was directed to report on the tracer method and to make recommendations for its possible use, either as a backup or as the primary method.[21]

Slowly, during the next several months, the centrifugal separator pulled ahead. Zero-g tests in November revealed that the two-bag system was seriously flawed. As 1971 began, Belew told Schneider that the one-bag system no longer seemed worth working on, and Houston decided that only the centrifugal separator would satisfy all major experimental and operational requirements. On 15 January, the three program offices agreed to drop the one-bag system and concentrate on the other two, which, they stipulated, must be interchangeable so as to simplify integration. Hamilton Standard, a firm that had worked with MSC in the Apollo program, was awarded a letter contract to develop the Langley separator. Belew notified Schneider that if neither system developed serious problems a decision would be made in September.[22]

By May, however, Stan McIntyre was convinced that the two-bag system was beyond salvage and recommended dropping it. In spite of changes in material and bag design, the filter was "basically unreliable and not suitable for Skylab." A review on 28 June showed that keeping the two-bag system, even as a backup, entailed a cost increase of at least $1.5 million. On 21 July Marshall ordered the workshop contractor to stop all work on the two-bag system. The centrifugal separator was selected in its place.[23]

Houston, meanwhile, had been working on the tracer method for volume determination. The principle is simple: a known quantity of a substance not normally present in urine is placed in each collection bag before use; after the bag is filled and the tracer thoroughly mixed, a sample is taken; the fraction of the tracer found in the sample is the same as the fraction of the total urine volume represented by the sample. If the sample contains 1% of the tracer element, then the sample volume is 1% of the total volume. Lithium was chosen as the tracer element. A small amount of lithium chloride would be put in each collection bag. As part of the normal processing procedure, the contents of the full urine bag would be recirculated through the centrifugal separator, thoroughly mixing the tracer with the urine. Having satisfied themselves that the method gave the accuracy they required, MSC's medical experimenters adopted it as the backup method to verify volume measurements made in flight.[24]

Compared to the urine system, the design of a collector for solid waste was simple. All feces were to be collected, vacuum dried—heating was no problem in this case—and returned for analysis. Again, Fairchild Hiller had developed a system for the Manned Orbiting Laboratory; this one proved satisfactory for Skylab. The collector was a plastic bag fitted with a porous filter to allow passage of air. It was enclosed in a holder beneath a toilet seat; behind the holder was a blower that pulled a current of air through holes in the rim of the seat, carrying the feces into the bag. The air from the blower passed through a deodorizing filter and back into the workshop. The bag was then weighed, placed in a processor where the feces were heated under vacuum to remove moisture, and stowed for return.[25]

Since the problems of separating air from liquid and of volume measurement did not arise with solid wastes, the fecal collection system was in good shape by the end of 1969. Its principal problem arose out of the difficulty of conclusive testing in zero g. The zero-g condition could be maintained for only about 30 seconds in the KC-135 aircraft, and the device had to be tested in that short period. Urination could be successfully simulated by mechanical devices, and a urine-collecting device was easy to test; but defecation could not be simulated. Test subjects who could perform on cue were needed. The Huntsville program office was able to find a few people with this talent, and in November 1969 two days of aircraft testing produced nine good "data points" for the fecal collector.[26]

Still, aircraft testing was not absolutely conclusive, and in January 1970 Marshall's Skylab office started lobbying for a flight of the fecal collector on one of the Apollo missions. In July the Apollo program office agreed to a test flight on *Apollo 14*, only to reverse that decision later in the summer. The unofficial account that got back to Marshall was that MSC's Skylab office supported the test, the astronaut office was officially indifferent to it, and the commander of *Apollo 14* flatly vetoed it. Marshall had to make do with aircraft testing.[27]

BUILDING THE MEDICAL HARDWARE

From the Marshall director's vantage point, building experiment hardware for MSC looked like a straightforward job. The Biomedical Task Team would fabricate some components in Marshall's shops (the ergometer frame and the shell for the lower-body negative-pressure device), contract for others, and assemble and test the final articles to Houston's specifications. The agreement hammered out by the two centers specified that Marshall would function "in the same manner as would any other contractor," with MSC managing the contract in the customary way. Missing, however, were the incentives and penalties that a NASA center could apply to a commercial contractor in a similar situation.[28]

Houston's medical directorate was responsible for management and technical direction of Marshall's task team, while the Skylab office retained "overall Center management including verification of requirements and resource management." The medical directorate supplied technical direction and information; integration requirements were to be exchanged through the two center program offices. As events of the next two years would show, this arrangement was unwieldy. Lines of authority and supply were complex, and it was sometimes difficult to tell exactly who was in charge at MSC. Management problems thus complicated the technical snags that Marshall's task team encountered.[29]

The critical experiment was M171, metabolic activity, which measured the body's rate of energy production while physical work was being done. A bicycle ergometer provided several calibrated levels of resistance against which the astronaut could work, while his energy production was measured by the ratio of carbon dioxide exhaled to oxygen inhaled. Building the ergometer presented no special problems, but the system to measure respiratory gases did. It required accurate flowmeters, precision valves, and a high-speed gas analyzer—all of them at the leading edge of technology and all of them interacting with a specialized computer and data-transmission system.[30]

Faced with a short development schedule for a complex set of experiments, Houston's medical directorate wanted to look at more than one design. For the gas analyzer the medics had settled on a mass spectrometer, an electromagnetic instrument that sorts out gases according to their molecular weights and determines the percentage of each gas in a mixture. During 1969, Marshall's biomedical task team was evaluating one mass spectrometer design while Houston's Skylab office was discussing another with Martin Marietta. In September a third choice entered the picture when MSC's Biotechnology Division found that a mass spectrometer was being developed by another office for another purpose and recommended that it be adopted for the metabolic analyzer.[31]

While the medical experimenters tended to let developmental work continue in the hope that one design would show clear advantages over the others, the Houston Skylab office had to meet a schedule. In April 1970, after the three designs had been compared, Houston program manager Kenneth Kleinknecht chose the design Marshall had been backing. Noting that this unit would meet the stated medical requirements and that a great deal of money had already been spent, Kleinknecht sought assurance that Marshall wanted to finish the job. When he got it, he stopped development work on the other two instruments.[32]

In early 1970 the other medical experiments were having a number of management difficulties. Marshall and Martin Marietta, the workshop integration contractor, could not agree as to who should integrate the Marshall-built medical experiments with the experiment support system, which was also a Marshall responsibility. Reporting to Huntsville's program office, Marshall's representative in Houston noted that the medical directorate and the Skylab program office at MSC were not communicating very effectively. And at Huntsville, Robert Schwinghamer's task team felt that the medical directorate was not coordinating its directions to them. Schwinghamer complained more than once that he was getting conflicting instructions from different people at MSC.[33]

Schedule pressures undoubtedly contributed to the confusion in the medical experiments program, because in July 1970 the medical directorate formally requested relief. As the schedule stood, development test units for the experiments—prototypes that would be tested to uncover faults in design or construction—had to be delivered in October 1971, 13 months before launch. Flight units, modified as a result of these tests, were required a month later. That single month was certain to be inadequate to correct deficiencies. The unrealistic schedule might well force compromises in design and testing, degrading the value of the experiments. The medical investigators expected, under those circumstances, that sooner or later they would be told to fly the experiments in whatever shape they were in, simply because it was launch time. In their view, however, the schedule should yield to mission objectives; there was no point in launching hardware that gave less than complete results. When the medical directorate proposed a launch delay, it was disapproved; but the deadline for the metabolic analyzer—the biggest worry—was relaxed to allow necessary testing, so long as delivery of the completed workshop was not delayed. The workshop contractor would have to work around the missing experiment as best he could.[34]

Reviewing the state of the medical experiments that summer, medical director Charles Berry and center director Robert Gilruth decided that some engineers were needed to improve liaison with Marshall. In September, Gilruth announced the appointment of Richard S. Johnston as Berry's deputy director for biomedical engineering and acting chief of a newly formed Skylab Project Support Office. Johnston had been chief of the Crew Systems Division in the early days of AAP, then special assistant to Gilruth for two years, and in 1970 was experiments manager for Apollo. After spending some time mastering the complexities of the management arrangements, Johnston brought in several engineers to expedite the translation of medical requirements into hardware. By the end of 1970, management problems were a much smaller annoyance than before.[35]

Marshall's first milestone was the production of design verification test units, which would be put through tests duplicating their expected use to discover deficiencies in design or construction. The verification testing was originally scheduled to begin in October 1970 and run until July 1971, but it actually began only in February 1971. In the next three months, six weeks of test activity were lost on account of failures in components supplied by MSC contractors. By mid-May Huntsville officials were expecting to resume tests shortly, but new requirements imposed by MSC promised to extend the test program into 1972.[36]

Assembly and testing continued through 1971, working toward a deadline of 15 January 1972 for delivery of all flight hardware to McDonnell Douglas. Troubles with electronic modules, however, continued to plague the project, notably the leg-volume measuring device manufactured by Martin Marietta. The metabolic analyzer, too, began acting up. By mid-summer 1971 only the bicycle ergometer and the lower-body negative-pressure device were comparatively trouble-free. In June, when MSC wanted two components removed from the metabolic analyzer test unit for examination by the manufacturer, Schwinghamer reported that this halted progress in the most successful test program to date.[37]

Late in September two "NASA alerts," agency-wide warnings about defective components, called attention to recently discovered malfunction of electronic parts, among them capacitors and integrated circuits similar to some already built into the metabolic analyzer. The capacitors were checked and replaced, but the integrated circuits—there were nearly 200 of them—completely stalled the program. Not enough acceptable replacements could be found anywhere in the country; delivery of new ones would take from 12 to 20 weeks. Testing went on with the units as built, but plans had to be made to replace the suspect components and retest the equipment further down the line. At year's end Huntsville notified McDonnell Douglas that flight articles would arrive 2 to 4 weeks late.[38]

Other factors now began to impinge on the medical experiments, particularly Houston's plans to simulate a 56-day Skylab mission, using the medical hardware. To be of any value, this had to be run well in advance of the first mission, and it required functioning experiment equipment. And at McDonnell Douglas's California plant, assembly and checkout of the workshop had reached a point where technicians were having to work around the missing medical hardware.

Late in January 1972, MSC requested authorization to postpone completion of tests and delivery of hardware as much as six weeks.

Schneider approved the request in part. Deliveries might be put off, but he would not agree to delaying the test program and told the centers to find a way to complete it. By now Schneider was contemplating dropping the troublesome metabolic analyzer altogether and asked MSC to estimate the impact of such a step. Both the medics and the program office objected vigorously; all the experiments were mandatory, and the metabolic analyzer's problems could be solved. Evidently Schneider accepted their evaluation, for the subject was not raised again.[39] Marshall found a way to substitute one metabolic analyzer unit for another so that the M171 equipment could be delivered in late February. Flight units of the medical equipment began arriving in California in February, the metabolic analyzer on 13 April. There was a lot of integration and testing yet to be done, but the hardest work was behind.[40]

A SIMULATION AND WHAT CAME OF IT

Since 1968 Houston's medical directorate had been considering a full simulation of a 56-day Skylab mission. Primarily the doctors were worried about changes in the microbial population when three men were confined in close quarters; they wanted no flare-up of bacterial infection, either during a mission or after the crews returned. Besides, a properly conducted simulation would give them one-g data from the medical experiments, useful in assessing changes brought about by weightlessness, and would check out the experiment procedures and equipment. Early in 1970 MSC petitioned Headquarters for funds to conduct a full-dress mission simulation.[41]

Houston's plans, however, were too ambitious for Headquarters' purse, and after some months of discussions a modified plan was submitted. Instead of two flight-configured Skylab mockups, MSC agreed to use an existing altitude chamber equipped with flight-type medical hardware and waste-management systems and using flight food. The bacterial ecology question was dropped; the new plan was intended to check out the hardware, establish baseline medical data, and verify experiment procedures and data-handling systems.[42]

After getting approval for this proposal in February 1971, the medical directorate got busy organizing the Skylab Medical Experiments Altitude Test, known thereafter as SMEAT, a pronounceable if unintelligible acronym. SMEAT was to be the only mission-length simulation in Skylab's entire experiment program, and Houston organized it thoroughly. A steering committee chaired by Richard Johnston oversaw the entire operation; four test-project managers were responsible for various aspects of the test, and they worked with medical teams, principal investigators, and flight operations and crew training personnel.[43]

Crew Systems Division's altitude chamber, which approximated

Skylab's size and shape, was configured to duplicate the orbital workshop as nearly as possible. The lower level was laid out with the wardroom and food preparation area, the medical experiments, and the waste management compartment. The one-g environment imposed some limitations; crewmen could not sleep against the wall as they would in flight, and the waste collection module had to be on the floor, not on the wall as in the flight workshop. The upper level, occupied in *Skylab* by stowed equipment and experiments, was used as a study area during the simulation. Since the medical experiments did not take up all of the crew's time, they planned to occupy their off hours by studying Russian and reading.[44]

Outside the test chamber, medical operations personnel would monitor the performance of the medical experiments, taking data just as they would during the mission. Communication with the crew was intermittent, corresponding to the actual times that *Skylab* would be in touch with a ground station.[45]

In mid-1971 a SMEAT crew of two pilots and a scientist was picked. Lt. Cmdr. Robert L. Crippen, USN, and Lt. Col. Karol J. Bobko, USAF, both ex-MOL astronauts who joined NASA in September 1969, became commander and pilot; they were joined by scientist-pilot William E. Thornton, a physician and biomedical engineer from the scientist-astronaut group picked in August 1967. Of the three, only Thornton was directly involved in Skylab at the time; he was one of the principal investigators for the small-mass measurement device to be used for weighing specimens in flight.[46]

After a year of preparation, Crippen, Bobko, and Thornton were locked into the chamber on 26 July 1972 for their eight-week stay. Since both crew and operations personnel had much to learn, there was no lack of activity to fill the time. It took a few days to get routine working relationships established and straighten out procedures. As would happen with the flight crews a year later, the SMEAT crew found that they got along well enough with each other, but developed a certain "us versus them" feeling toward those outside. Most of their problems were normal and predictable: poorly-fitting medical sensors, lack of familiarity with some equipment, procedures that had to be modified; and these were ironed out. The crew found the environment tolerable if not luxurious, the food good if not exciting. There was plenty to do and no idle time to speak of, though they did find time for an hour or so of TV a day—commercial channels were available—and they could call family and friends on an outside telephone line.[47]

Though most of the problems in SMEAT were small and easily corrected, some very big ones proved the simulation's value. In the very first days the bicycle ergometer broke down and the metabolic analyzer was consistently erratic. Worse yet, the SMEAT crew uncovered faults in the urine collection system that threatened to require substantial redesign of the whole unit.[48]

With launch only nine months away, MSC and Marshall immediately began troubleshooting the ergometer and the metabolic analyzer. The ergometer failure proved to be a mechanical design problem unique to the test unit; when this was corrected it functioned as intended. (Still, the other units—one of them already installed in the workshop—were torn down, examined, and rebuilt, and spare parts were included in the flight inventory.) The metabolic analyzer's problems were more complex, involving both mechanical and electronic failures. A meeting in late September prepared a list of essential changes and tests, and Marshall began reworking the units.[49]

Problems with the urine system were potentially very serious. The two-liter collecting bags were too small. Indications of this shortcoming showed up in pre-SMEAT activities; and during the simulation it turned out that one crewman's normal daily urine output was nearer three liters than two, and both of the others produced more than two liters occasionally.* This was not a problem for the SMEAT crew because they had other toilet facilities, but it was desperately serious for the engineers. The urine pooling bag and its mechanical accessories took up every cubic centimeter of the space allotted to it. Increasing its capacity looked all but impossible.[50]

A second SMEAT problem was, from the crew's point of view, even worse. The urine centrifuge leaked, and the collection unit could not be cleaned up completely. On six occasions, collection bags were torn in handling, dumping a liter or more of urine into the waste-collection unit, onto the floor, and onto the crewman. Astronauts were already concerned that the system seemed too complex and had not been adequately tested in zero g; these urine spills were very nearly the last straw. Pete Conrad, who would command the first Skylab mission and who was in training at the time, lost all confidence in the system. He began working with Houston engineers to adapt the system that was about to fly on *Apollo 17* and indicated that he was quite prepared to abandon the Skylab system entirely. For a time, relations between engineers and crew representatives were strained.[51]

Meanwhile, tests at McDonnell Douglas had turned up an entirely unrelated defect in the urine system. The in-flight volume-measuring system, a complex device with a pressure plate and several mechanical linkages, did not meet the accuracy requirements. With launch now only six months away, the urine system seemed to need complete redesign, or the medical requirements had to be reconsidered—or both.[52]

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* The bag size was based on physiological norms, not on measurements taken with crewmen. When the system was designed the crews had not been selected. Requests by medical investigators to measure 24-hour urine output for the astronauts were turned down by the astronaut office because it would interfere with training. Carolyn Leach interview, 3 Dec. 1976.

A week after SMEAT ended, a telephone conference between Headquarters, Houston, and Huntsville led to agreement on expanding the urine system's storage capacity to four liters. Three options for design modifications were defined for study, two of which bypassed the centrifuge entirely and relied on the *Apollo 17* system. Two weeks later, however, a consensus developed for a two-way system, using a four-liter bag but giving the crew a choice of collecting devices, the Skylab centrifuge or the Apollo roll-on cuff.* It was generally agreed that measurement of volume in flight could be dispensed with, since the lithium chloride tracer technique was adequate. These changes allowed the urine collection drawer to be simplified, leaving room for the larger bag as well as a protective metal box to enclose it. Mixing the 24-hour pooled urine, however, would have to be done by kneading the bag by hand rather than by recirculating its contents through the centrifuge. By 15 November, three and a half months after the problems came to light, an acceptable design was critically reviewed and modifications were going forward.[53]

Commenting on the significance of SMEAT at its conclusion, Dick Johnston expressed the conviction that it saved the program, since serious operational problems would have come up in flight with no way to solve them. Both he and Ken Kleinknecht acknowledged the problems to the press, but both were sure that they would be worked out. When the waste management system finally flew, the grueling four months of work after SMEAT paid off. The urine system and the medical hardware worked exactly as required. Redesign of the urine system was justified, because two crews had at least one member who consistently excreted more than two liters of urine a day. Experienced crewmen found the system a great improvement over what they had used before. The rookies, who had heard all the horror stories about waste management, were pleasantly surprised. And after all the tumult and shouting, Pete Conrad took particular care to compliment the engineers on an outstanding system.[54]

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* This was a rubber tube that functioned as an external catheter and was attached to a collecting bag. It amounted to a heavy condom. R. S. Johnston, L. F. Dietlein, and C. A. Berry, eds., *Biomedical Results of Apollo*, NASA SP-368 (Washington, 1975), p. 475.

9

Studying the Sun

Skylab's major nonmedical scientific project was the Apollo telescope mount, which became a part of the program in 1966. The most complex and expensive of the scientific programs and the most demanding in terms of technical requirements, the ATM had been allotted one of the three AAP missions (pp. 55, 74). When the decision was made to launch the solar observatory along with the rest of the cluster, its peculiar requirements dictated many features of the orbital assembly and the missions.

SOLAR INSTRUMENTS

With its four solar arrays extended like the sails of a medieval windmill, the Apollo telescope mount was the most striking feature of the orbiting *Skylab*. At the hub of the arrays was the canister carrying the six major instruments making up the solar observatory. (App. D tabulates information on all experiments.) Five of these measured radiation in the high-energy ultraviolet and x-ray regions of the spectrum—radiation that does not reach the earth's surface because it is absorbed by the atmosphere. The sixth photographed the sun's corona, a tenuous body of gas whose faint light is blotted out for observers on earth by the brilliant light of the solar disk, scattered by the atmosphere.*

From a study of the wavelength and intensity of x-rays and ultraviolet radiation, scientists could deduce the composition, density, and temperature of the region under study. Photographs of the corona would provide information about its motion, physical state, and magnetic environment and would relate changes in the corona to events at the sun's surface. This information, scientists believed, would help them under-

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*The corona can be studied from the earth during total solar eclipses, or by use of coronagraphs at high altitudes, where the atmosphere is thinner.

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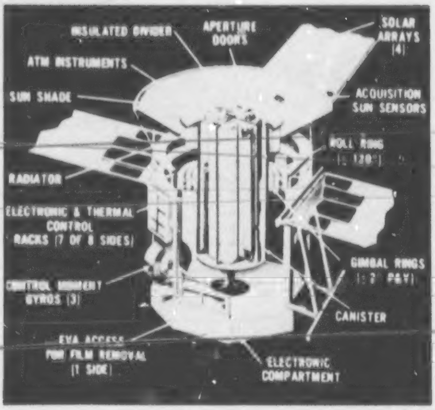
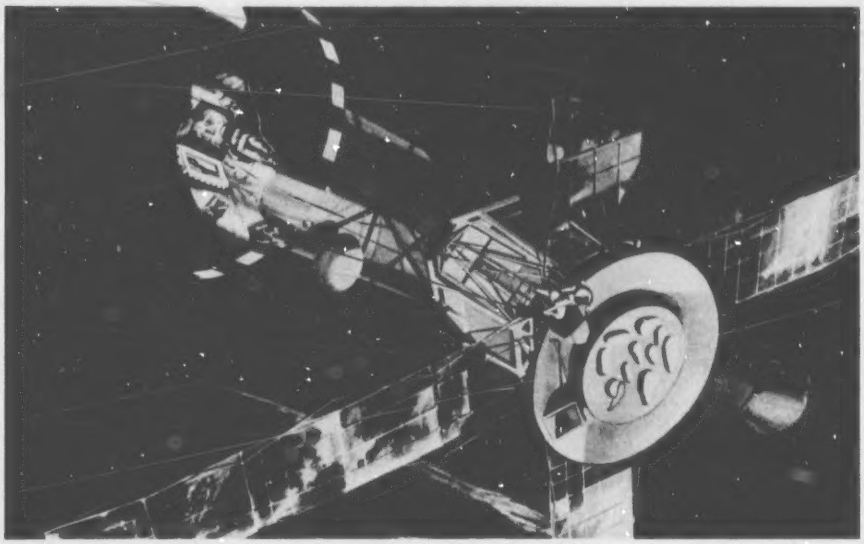

INSULATED DIVIDER
APERTURE DOORS
SOLAR ARRAYS (4)
ATM INSTRUMENTS
SUN SHADE
ACQUISITION SUN SENSORS
ROLL RING (± 120°)
RADIATOR
ELECTRONIC & THERMAL CONTROL RACKS (7 OF 8 SIDES)
GIMBAL RINGS (± 2° P&Y)
CONTROL MOMENT GYROS (3)
CANISTER
EVA ACCESS FOR FILM REMOVAL (1 SIDE)
ELECTRONIC COMPARTMENT

The Apollo telescope mount as depicted on a 1972 briefing chart. MSFC-72-PM 7200-115A.

stand the processes by which energy is transferred from the sun's interior out into space. To get that information, solar physicists needed instruments with high resolution, pointing accuracy, and stability. Such characteristics had to be designed into the telescopes and their supporting systems from the start.[1]

Though initially conceived for use on the Advanced Orbiting Solar Observatory, the ATM instruments were general-purpose telescopes; with suitable modifications, they could be used on other missions. The major change made when the instruments were moved to the ATM was to convert them to photographic recording (all except Harvard's ultra-

Changing film at the Apollo telescope mount, a briefing slide from late 1970. The viewing ports for the various instruments are on the raised center of the white circle. S-71-48024.



violet spectrometer). Film gave better spectral and spatial resolution* than photoelectric recording, but photoelectric instruments could record a wider range of intensities and had a shorter response time. Since film had to be replenished during the mission, this decision made all the experiments except Harvard's dependent on the astronauts, who would recover exposed film and reload the cameras during extravehicular activity. It was a bold step to take in 1966, when working outside the spacecraft was still a questionable area of manned spaceflight and when early experience in Gemini had not been encouraging.[2]

To assist the human operator of the solar telescopes, several accessory instruments were added to the ATM in the later stages of design. A monitor measured the total x-ray output of the sun, a useful index of overall solar activity. It was connected to an audible alarm, set to go off when a predetermined high level of x-radiation was exceeded, alerting the crew that a solar flare might be imminent and that the control panel should be manned. Another monitor displayed an image of the sun in ultraviolet radiation and similarly served as a means of locating active solar regions. In 1968 two pointing-control telescopes were added to the instrument package. Equipped with filters to pass a single wavelength, the red-orange light in the spectrum of incandescent hydrogen, these hydrogen-alpha or H-alpha† telescopes revealed much of the fine granular structure of the sun's surface, which they displayed on a television monitor at the control panel. Both had variable focal length (zoom) lenses and cross-hairs to enable precise pointing of the other instruments, with which they were aligned. Cameras provided a permanent record of where the H-alpha telescopes were pointed when observations were taken.[3]

The experiments and their supporting systems were designed to be nearly independent of the carrier vehicle—until 1969, a modified lunar module, whose ascent stage provided a pressurized cabin with room for two crewmen and a control and display console for the instruments. When the lunar module was discarded in the change to the dry workshop, some changes to the ATM were required. It was moved onto a supporting structure above the multiple docking adapter, its pointing system was modified to control the entire workshop, and the control panel was moved into that now-vacant module. The instruments were scarcely affected by this change, and their development, which was well under way by the end of 1968, was hardly perturbed.

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* *Resolution* refers to an instrument's ability to separate closely spaced lines in the spectrum, to separate the images of adjacent points on the sun, or to respond to two separate events closely spaced in time.

† This red-orange light (wavelength 656.3 nanometers) is the first (longest wavelength) line of the Balmer series in the hydrogen spectrum, hence the designation.

APOLLO TELESCOPE MOUNT

The solar telescopes were massive—the entire collection weighed over a ton and some of them were three meters long—but they were still precision optical devices, requiring elaborate support systems. Primary among the requirements was the ability to aim the instruments precisely at any desired point on the sun and hold them there in spite of disturbances to the orbital assembly. Another was strict control of temperature. To preserve the alignment of its optical elements, the Naval Research Laboratory's telescope had to be kept within 1.5°C of the temperature at which it had been calibrated, and the temperature could not change more than 0.005°C per minute—all of this while the instrument canister was exposed to the full blast of unattenuated solar radiation. Then there was the matter of using the human operator effectively, automating as many operations as possible while still allowing him to use judgment and make on-the-spot decisions about what should be observed and which instruments used. Finally, systems such as electrical power and data management, if not as challenging as some of the others, were no less essential.[4]

Responsibility for these supporting systems, which with the structure that supported the canister made up the Apollo telescope mount, fell to Marshall (p. 75). Apollo Applications Program Manager Leland Belew established an ATM Project Office in July 1966, with Rein Ise as project manager. Ise, whose tenure dated back to pre-NASA days with the Army Ballistic Missile Agency, was one of several engineers who came to AAP from the defunct Saturn IB–Centaur program. Marshall's Astrionics Laboratory would build parts of the mount, contract some of the systems out to industry, and assemble the test, prototype, and flight articles.[5]

Besides the test and flight hardware, engineering simulators and training mockups were required for design work and crew training. By mid-1968, Marshall had built a control and display simulator on which engineers worked out the switches, controls, and computer logic. Later, this simulator was upgraded to provide computer-generated displays simulating the observations that would be made in flight; it was then used by crews and engineers to develop and verify inflight operating procedures. Simulators for the power, attitude-control, and pointing-control systems were also being built in 1968. Training hardware included a one-g trainer, a full-scale mockup of the entire mount (except for the solar power arrays) with functional work stations, and a mechanically functional control and display console. There was also a zero-g trainer, consisting of mockups of the work stations that could be flown in a KC-135.[6]

Zero-g testing was critical to the ATM design. Film cameras attached to the telescopes contained all of the experimental data (except for that from the Harvard instrument), and they had to be retrieved by the crew working outside the vehicle. This requirement produced close collaboration between Houston and Huntsville; astronauts frequently conferred with engineers and tested designs of the work stations where film cameras were removed and replaced.

For this kind of design work the 20–30 seconds of zero gravity obtainable in aircraft were inadequate. The best alternative was working under water, with the subject's arms, legs, and body carefully weighted until they were neutrally buoyant, neither sinking nor floating. This technique had been used in preparing for Gemini, and in the early days of the Apollo Applications Program Marshall had done some neutral buoyancy design work in a water tank once used for explosive forming. In 1968 the center was putting the finishing touches on a new Neutral Buoyancy Facility expressly designed for the purpose—a tank 22.8 meters in diameter and 12 meters deep, in which full-size mock-ups of cluster components could be immersed. The new tank was built primarily as a design aid for Marshall engineers, but later in the program it also became an important crew training facility. Underwater simulation of zero g was not perfect, but astronauts found that anything they could do in the tank could generally be done in orbit. Better still, underwater simulations were conservative; they required more effort than the same task required in space and therefore did not lead to underestimating the difficulty of a task.[7]

Instruments with the capabilities of the ATM solar telescopes had never been flown on manned spacecraft, and their requirements placed severe demands on systems in the cluster. Pointing accuracy requirements were unprecedented; the instruments had to be pointed within 2.5 arc seconds of the desired spot and held there without drifting more than 2.5 arc seconds in 15 minutes' time. (A quarter, viewed from a distance of a kilometer, is about 2.5 arc seconds in diameter.) Conventional thruster engines for attitude control could not be used; they were insufficiently delicate, they required too much fuel for long missions, and their exhaust gases would interfere with optical observations. From 1966 onward, the attitude control system for the solar observatory was based on control moment gyroscopes.

A control moment gyroscope (CMG) is, as the name implies, a gyroscope large enough to impart controlling moments or torques directly to a spacecraft.* Engineers often called them "momentum exchange" or "momentum storage" devices, meaning that the turning motion produced by external forces acting on the spacecraft could be transferred to the gyroscopes rather than moving the spacecraft itself. Three CMGs, each with a 53-centimeter rotor weighing 65.5 kilograms and turning at about

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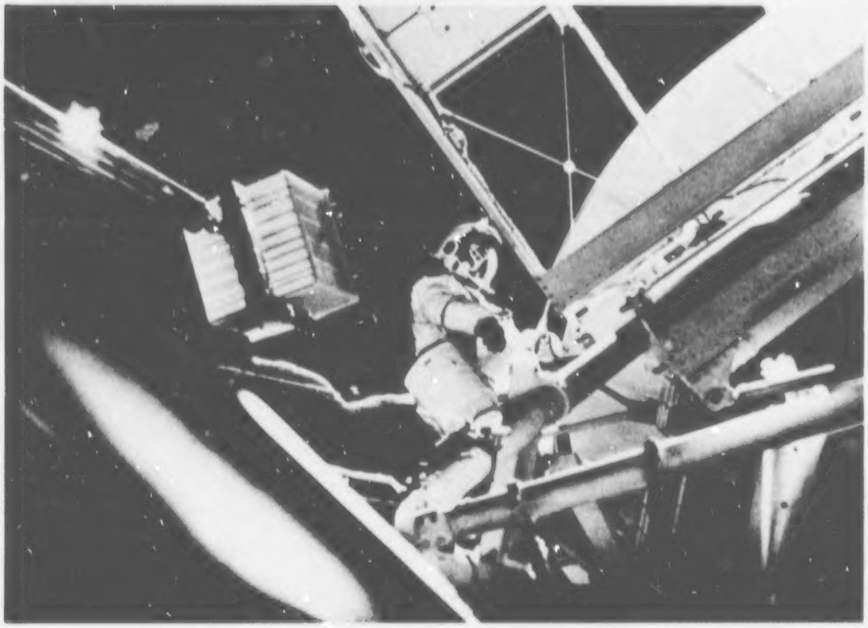
* The gyroscopes ordinarily used in guidance and navigation systems are much smaller; they function by generating electrical signals that in turn activate attitude control systems.

Practicing the retrieval of film from the telescope mount in Marshall's Neutral Buoyancy Facility, left. MSFC 027034. *The film magazine is on the end of the boom; the white flotation collar near it provided neutral buoyancy. Below, the task being performed in space.* 73-H-979.



9000 rpm, were mounted on the ATM support structure. Any two could control the cluster; the third provided the required redundancy. Each was mounted in two gimbal rings that could rotate around two axes.[8]

Control moments were generated by exerting a force on the gimbals. Any attempt to turn the gimbal of a spinning gyroscope produces a seemingly anomalous motion: force applied to the outer gimbal results in motion of the inner one, the gyro rotor moving at right angles to the applied force and its own axis. At the same time a reactive force opposes the force applied at the outer gimbal, and since the gimbal is attached to the spacecraft framework, this reactive force turns the cluster around one of its axes.

Coupled with the CMGs was a set of sensors that determined the cluster's attitude with respect to the sun and the horizon, as well as the cluster's rate of rotation. A sun sensor and a star tracker determined attitude errors, while rate-sensing gyroscopes determined how fast the vehicle was turning in each of three directions. Signals from these sensors went to the ATM's onboard digital computer, which calculated the necessary changes in attitude and sent corrective commands to the CMGs. Torque motors on the gimbals applied a precisely controllable twisting force, the gyro rotors moved to new positions, and the spacecraft remained in the desired orientation. The net effect was to transfer the rotational motion of the workshop (its angular momentum) to the gyroscopes.[9]

For observations with the solar telescopes it was necessary to point the instrument canister directly at the sun and hold it there as long as possible. When the spacecraft came out of the earth's shadow, the attitude control system pointed the canister at the sun, with the vehicle's long axis in the orbital plane, holding it there until the workshop was about to enter the dark side of its orbit again. This "solar inertial" attitude was the one in which the spacecraft would spend most of its time, and the electrical power and temperature control systems were designed on that basis.

There were several sources of unwanted motion for the orbital assembly. Crew motion within the vehicle would produce small random forces; aerodynamic drag, though small at orbital altitude, would still be appreciable. The largest perturbation, however, was produced by gravity, which acted unevenly on a large unsymmetrical structure like *Skylab*. While the spacecraft's center of mass faithfully followed the prescribed orbit, the heavier end was pulled toward the earth more strongly than the lighter. This gravity-gradient torque caused the cluster to turn slowly around its center of mass. Part of this torque could be eliminated by properly positioning the spacecraft in the plane of its orbit, but that solution was limited by the necessity to point the telescopes at the sun. The residual gravity-gradient torque and aerodynamic drag produced a net rotation that the CMGs had to absorb.

The CMG system was capable only of coarse pointing—within 6 arc minutes (0.1 degree), two orders of magnitude larger than the instruments required. Mechanical constraints limited the travel of the CMG gimbals; and after a long period of absorbing unwanted torques, the CMG rotors reached a position of saturation, an alignment in which no further correction could be produced. When all of the CMGs became saturated they could no longer control the spacecraft until the rotors were returned to their original position. A way had to be provided to "desaturate" the gyroscopes during periods when the solar instruments were not in use.[10]

For this purpose engineers used the same force that caused saturation in the first place: gravity-gradient torque. As the orbital assembly entered the dark side of its orbit, the ATM digital computer—the most sophisticated ever put on a manned spacecraft—determined the degree of saturation and commanded a maneuver into an attitude such that the gravity-gradient torque would return the gyros to their original position in time for the next sunlit portion of the orbit. Maneuvering for this procedure (called *momentum dumping*) was accomplished by the thruster attitude-control system.[11]

For the fine-pointing control required by the telescopes, the spar on which the instruments were mounted was suspended inside gimbals. The gimbal rings could be moved two degrees up or down and left or right; they were mounted inside a roll ring to enable rotation around the long axis of the canister (the sun line). The entire fine-pointing assembly was suspended by frictionless flexible pivots capable of damping out small disturbances. Each degree of freedom was controlled by a fine sun-sensor and rate gyroscopes that normally pointed the instruments within 2.5 arc seconds of the sun's center. On the control panel was a joystick—much like an airplane's control stick—which activated an optical device in the fine sun-sensor, permitting accurate offset pointing of the canister to any point within 24 arc minutes of the sun's center.* [12]

The wet workshop was to have depended on an auxiliary attitude-control system powered by chemical fuels for use on the first three manned missions and CMGs for the fourth, the ATM flight. For the dry workshop, engineers adopted a thruster attitude-control system powered by compressed nitrogen. It was simpler than chemically powered systems and did not contaminate the space around the solar telescopes, but it was heavier—a penalty that was accepted in view of the system's advantages. Twenty-two spherical tanks around the S-IVB's thrust structure fed gas to six thrusters (two in each axis) in the stage's aft skirt. These thrusters provided the force required in docking and maneuvered the spacecraft when the CMGs could not manage the task.[13]

The attitude and pointing control systems were Marshall's responsibility, but MSC astronauts would have to operate them, so early in 1967 an intercenter task team was formed to work on the crew's interface with the solar experiments, among other problems. The Houston members were dissatisfied with Marshall's proposals for the ATM control panel; it looked more like a system for an unmanned spacecraft than for a manned one. MSC wanted more information provided to the ATM operator and more participation by him in the control of spacecraft systems. Houston particularly objected to Marshall's digital-address system, whereby control commands were entered into a computer by punching 5-digit numbers into a keyboard. If man was as important to the solar observatory as everybody insisted, Houston believed he should do more than relay numbers to a computer and monitor a few status indicators. In August 1967, Bob Thompson collected MSC's comments on the control-panel design and forwarded them to Lee Belew, recommending a number of changes and spelling out MSC's philosophy for panel design.[14]

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* The sun's angular radius is about 18 minutes of arc, hence the instruments could be pointed at regions as far out as 1.3 solar radii without using the CMGs.

Five months later, however, a preliminary requirements review showed that the two centers were still not in agreement. Though an MSC representative had been working closely with Marshall designers, the Houston review team strongly disagreed with several concepts—once more concentrating on the digital-address system.* A complete redesign of the control and display system seemed necessary, and a working group was established to resolve the differences. By mid-May, working with astronauts and the contractor, the group had a concept that reasonably satisfied everyone, and detailed design work could go on.[15]

The control and display panel that resulted was probably the most complicated ever put into a spacecraft. It had three times as many controls as the Apollo command module; one ATM experimenter thought it was "at least as complicated as one for a large aircraft." Painstaking design work, however, produced a control center that was highly functional and not inordinately difficult to operate. The exact status of each instrument was displayed to the operator, along with information on the workshop's attitude and orbital position and the condition of the ATM power system. Two television screens displayed the sun as seen through the H-alpha telescopes; another displayed the coronagraph's field of view, and a fourth the x-ray monitor. The logical design put all instrument controls, attitude and pointing controls, and telemetry within arm's length of the seated operator.[16]

MISSION PLANS AND OPERATING PROCEDURES

With experiment development reasonably well in hand, the ATM scientists turned their attention to other matters in 1969. Operational procedures—when and how the instruments would be operated, how much observing time was allowed, how rigid the flight plan would be—were of primary concern during the next two years. No one had any experience with missions quite like Skylab. The astronomers, experienced with sounding rockets and unmanned missions devoted to a single set of experiments, now found themselves competing with medical experiments for operational time. Flight controllers who were used to having total control over communications with the spacecraft now had to deal with experimenters who insisted on talking directly with the astronauts.

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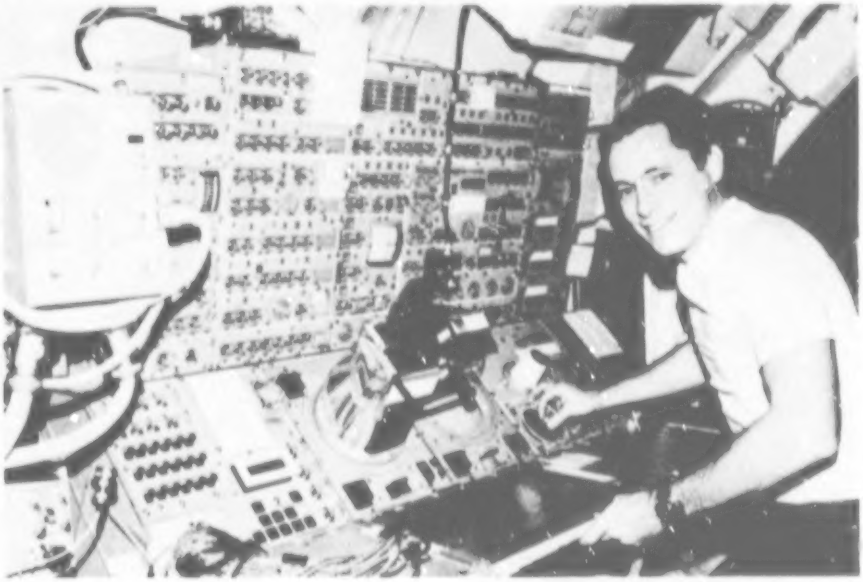
* Gilruth told von Braun that "the old test pilot types . . . are just more in favor of mode selector switches than the more scientifically inclined scientist-astronauts." Von Braun's handwritten annotation on Haeussermann's "Notes" of 29 Jan. 1968.



Astronaut Edward Gibson at the control and display console for the Apollo telescope mount, above. S-74-17306. *His hand is on the joy stick that aimed the solar instruments, as indicated by cross hairs in the hydrogen alpha telescope, right.* 108 KSC-73P-434. *Gibson was scientist-pilot on the third crew; this solar flare was photographed by the first crew.*

Not only that, the experimenters wanted to be able to change the flight plan every day—even oftener, if the capricious sun unexpectedly spouted flares. The flight controllers' ideal mission—never realized, to be sure—was nicely predictable and offered just enough of the unusual to challenge their ingenuity. The scientists, on the other hand, needed to be able to adjust their observing program to unpredictable events, to change the mode of operation of each instrument as conditions indicated, or to drop everything else and watch the sun for several orbits if something really interesting was happening. Moreover, the scientists never hesitated to complain to NASA's top management when things did not go to suit them.

Operational questions were a major subject at a principal investigators' meeting in April 1969. E. M. Reeves, representing the Harvard College Observatory, wanted to know how priorities would be assigned to the telescopes and who would resolve any conflicts that arose. Marshall's experiments manager assured him that Martin Marietta was devising a computer program to distribute observing time equitably, and Martin would brief the astronomers. Reeves then expressed concern that MSC was not giving Skylab operations enough attention. Assured that Skylab would get higher priority once MSC had landed the first men on the moon—three months away, if all went well—Reeves then urged that planners provide direct communication between principal investigator and astronaut at least once a day. Such free-ranging conversations were not normally allowed on manned flights. When Houston's representative invited the astronomers to visit the Mission Control Center during one of the upcoming Apollo missions, to see how manned flight operations were conducted, Reeves rejoined with an invitation to flight controllers to Cambridge, where they could learn how scientific missions were run.[17]

Late in 1968 Harvard proposed to change the cluster control system so that its instrument, the only one that produced data in real time, could be operated from the ground during unmanned periods. In effect, they wanted to add all the capabilities of unmanned instruments. When Marshall's preliminary tradeoff studies showed a large cost and schedule impact, Program Director Bill Schneider demurred, but Harvard's principal investigators persisted, seeking support from other ATM investigators. Three of the other four project scientists indicated that they, too, would like some unmanned operating time; and despite Marshall's insistence that the proposals were not feasible, additional studies were ordered. Again Marshall showed that large cost increases and long schedule delays would result. They convinced the program manager from the Office of Space Science and Applications, but not the scientists, who were certain the studies were (perhaps intentionally) too pessimistic. In mid-December, however, the Harvard astronomers finally agreed to accept substantially less than they had originally asked for, and Schneider agreed to preserve the option of unmanned operation; he stipulated, however, that there must be no hardware changes costing more than $50 000 and no schedule delay, and that both the Space Science and Applications Steering Committee and the Manned Space Flight Experiments Board must approve any change before he would accept it.[18]

Already unhappy over the loss of the second ATM flight that George Mueller had promised them in 1967 (p. 90), the solar scientists were annoyed in July 1969 by the dry-workshop decision. Both Leo Goldberg and Gordon Newkirk complained to Mueller that they had been given no chance to evaluate the effect of that change on their scientific programs. Mueller tried to placate them by explaining the advantages of the dry workshop, including a higher probability of success for the ATM mission and considerably more observing time; but the failure to consult rankled, all the same.[19]

Another surprise was in store for the ATM scientists later in the year, when they learned that Headquarters was about to add a group of earth-sensing experiments to Skylab—another example, to astronomers, of Mueller's tendency to make major changes without consulting those whose experiments would be affected. Not only would these new experiments compete with ATM for crew time; they would require holding the cluster in an attitude that precluded solar observations. The film and tape they used would add to the load in an already overloaded command module. This new disturbance, coupled with the fact that observing-time allotments for the dry-workshop missions were still unsettled, prompted the astronomers to request immediate attention to operational procedures.[20]

At a meeting in late September 1970, ATM experimenters and MSC officials discussed Skylab operations, which Houston intended to conduct in much the same way it had run its previous missions. Experimenters would specify the observations they wanted carried out and the time they wanted spent on them; the flight operations office would impose the many operational constraints; and after the usual reiterated tradeoffs, a flight plan acceptable to both the scientists and mission controllers would be laid down. During the missions, changes to this agreed plan would be passed through a long chain of command and relayed to the spacecraft by the CapCom. While this might have worked for many types of experiments, it was unsuited to studying the sun—mainly because the sun was unpredictable, but also because experimenters wanted to base later observations on the results of earlier ones. When OSSA's representative pointed out that a few really good photographs were worth more than a lot of uninteresting ones, Houston promised to work with the astronomers to assure success on the scientists' terms.[21]

While this early encounter with operations personnel was encouraging to the scientists, their first look at the computerized time allotments produced by Martin Marietta was not. Nobody was totally satisfied with the program; Richard Tousey of NRL found it unacceptable. In response to Tousey's protests, Marshall's experiments manager acknowledged the program's shortcomings, but assured NRL's principal investigator that further refinements by Martin Marietta's experts would improve it. The principal investigators, however, decided to take matters into their own hands. Without informing NASA officials, the investigators devised a time-sharing plan that would make best use of their instruments. After listing the most important problems in solar physics, they selected those to which the ATM instruments were expected to contribute significantly. From this analysis a set of procedures was developed that would make use of every instrument during all the time allotted to solar observations. At first they called this the Program Oriented Observing Program, but when the humor in the acronym grew stale they changed it to the Joint Observing Program. In time there were 13 programs (table 1), each with a set of defined objectives, a list of the data required to satisfy the objectives, and a list of building blocks—sequences of instrument operation—that would gather the necessary data.[22] (Joint Observing Program 2, Active Regions, is reprinted as app. G.)

When the scientists presented their plan at a meeting late in March 1971, it was NASA's turn to react indignantly to an unexpected change

Table 1. Joint Observing Programs (August 1971)

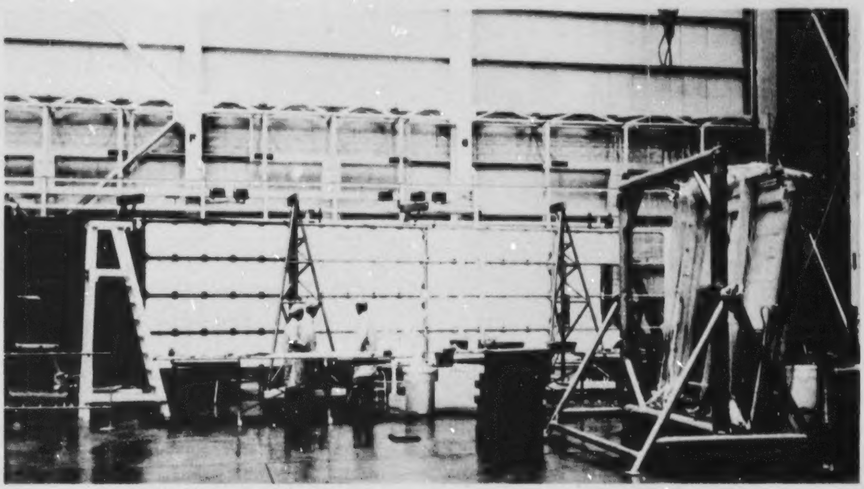
1. Study of the chromospheric network and its coronal extension
2. Active regions
    - A. Rapidly developing active region
    - B. Long-term evolution of an active region
    - C. Structure of an active region
    - D. Sunspots
    - E. Chromospheric velocities
3. Flares
    - A. Flare-centered pointing
    - B. Non-slewing flares
    - C. Limb flare
4. Prominences and filaments
    - A. Evolution of filaments and prominences
    - B. Structure of a prominence
    - C. Structure of a filament
5. The sun's atmosphere as derived from center to limb variation
6. Synoptic observations of the sun
7. Atmospheric extension
8. Coronal transients
9. Solar wind
10. Lunar librations
11. Instrumental calibration
12. Solar eclipse
13. Stellar observations

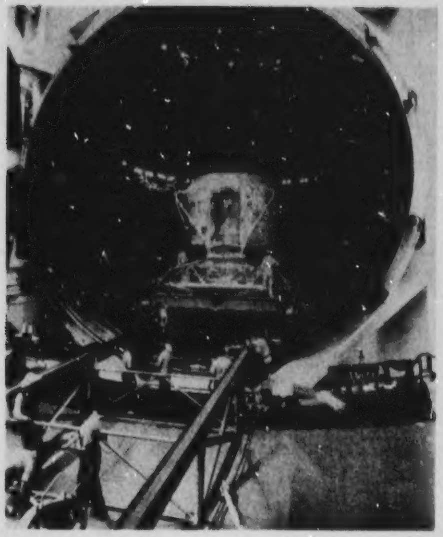
proposal. KSC's representative pointed out that adopting the scientists' proposal would mean scrapping the work that Martin Marietta had already done, and perhaps even rewriting the mission-requirements document—both, apparently, unthinkable at that stage. The astronomers, believing no one could plan better use of their instruments than they themselves, stuck by their proposal. With the help of some engineers in mission planning at Houston, the scientists got their observing programs adopted as the basic mode of operation for the solar instruments.[23]

TECHNICAL PROGRESS AND PROBLEMS

Work on the ATM instruments and supporting systems progressed smoothly during 1969. Critical design reviews were completed on all of the instruments, on the solar-cell wing assemblies, the ATM control computer, and the star tracker. Qualification tests on a number of experiments and support systems were completed, and by the end of the year Houston's thermal vacuum chamber was being prepared for tests on the ATM. An assessment of the project in January 1970 showed that, except for the prototype instruments, the solar observatory was generally on schedule. The situation was helped by postponement of launch date from July to November 1972, which allowed for hardware delivery to the Cape in November 1971. Another review on 11 March 1970 showed no problems that could delay the schedule, though some subsystems required close attention to keep them on track.[24]

A solar wing for the telescope mount being assembled. At right, a completed wing is stored in its launch configuration. ML71-7321.





The telescope mount, constructed at Marshall Space Flight Center, undergoing thermal vacuum testing at Manned Spacecraft Center in July 1972. 72-H-1040.

By the middle of the year, however, an accumulation of niggling problems was having an effect. After an ATM review 11–12 August, KSC's representative was pessimistic about the project, noting that the wet-to-dry change and the scientists' predilection for tinkering with their instruments had produced "near chaos" in the configuration control system. Already, delivery of the flight unit had slipped 18 months, and the addition of the unmanned capability could be expected to delay the ATM even more.[25]

If the KSC official was unduly pessimistic, the reason probably reflected that center's enormous work load in checking out the entire cluster. Furthermore, checkout problems always looked more serious from Florida than they did from Alabama. Generally, the experiments were doing well in 1970; by the end of June, four of the five instrument prototypes had been delivered and were in storage at Huntsville. Persistent problems did exist, however; S082B had trouble with its electronic assemblies and film cameras, and the zoom lenses for the H-alpha telescopes would not always focus properly. Then in July, testing of S082A revealed serious deterioration of its spectrograph grating; replacement would take time. In spite of some schedule relief at the end of August, when the target launch date (July 1972) was officially dropped, all of the ATM instruments were having problems. NRL's two S082 instruments would be delivered late, and Marshall was having trouble finding money to complete the test program.[26]

Much of the pressure on the ATM was relieved in January 1971, when Headquarters postponed the last Apollo flight (*Apollo 17*) to ensure that it would carry an optimum load of experiments. Skylab was put off again, this time for four and a half months; when the last launch-readiness schedule was published on 13 April, the new launch date was 30 April 1973. Experiment problems were no longer a threat to the schedule, but they continued to demand attention.[27]

In May, after passing its acceptance review, experiment S082B showed serious deterioration in its response to short wavelength radiation. Examination of its optical components revealed that its main diffraction grating was afflicted with "purple plague," a condition resulting from an unexpected chemical reaction between the gold coating of the grating and the aluminum coat applied over that. The grating had to be replaced, causing an eight-week delay that took all of the cushion out of the ATM delivery schedule.[28]

At the end of 1971 a midterm review of the entire Skylab program gave grounds for cautious optimism. The ATM posed no serious problems, but the project manager's overall assessment was that no time remained to take care of major problems. Everything had to go right from then on. The flight unit could be delivered to Kennedy Space Center by 1 October 1972, as scheduled, but it was going to take constant hard work to make it. In that respect the ATM was in much the same shape as the rest of the cluster.[29]

Only one serious anomaly showed up in ATM testing, and that one had to some extent been anticipated. Thermal vacuum testing at MSC in August and September resulted in failure of one of the control moment gyros, caused by inadequate lubrication. This defect had been suspected earlier, and backup units with better lubricating systems were substituted. The ATM flight unit was flown from Houston to KSC on 22 September 1972, the same day that the orbital workshop arrived by barge from California. Final checkout and mating with the other cluster components were ready to begin.[30]

10

Late Additions to the Experiments

Solar astronomy and space medicine were major experiment programs, and together with the so-called corollary experiments they were certainly adequate to fill the operational time available on the Skylab missions. They were also about as much as the program could comfortably accommodate and still launch on time, a point particularly stressed by program officials at Marshall Space Flight Center.

But when the Office of Manned Space Flight chose to develop the Shuttle as its next major program, Skylab was left as the only manned program that would be flying for an uncomfortably long time. For all of Headquarters' stipulations that only mandatory changes were to be made after the dry-workshop decision, there was a natural tendency to use this last set of missions to best advantage. Besides a number of changes in the workshop (pp. 123–24, 144–48), one major and one minor group of experiments were added between July 1969 and January 1973.

OBSERVING THE EARTH

Cancellation of Apollo Applications mission 1A at the end of 1967 seemed to put an end to any possibility that Skylab would conduct studies of the earth (pp. 87–88). Yet within two years the Skylab program office was preparing to add a set of complex and expensive instruments for that very purpose. Those two years had seen a tremendous upsurge of interest in remote sensing and its practical applications.[*] Increasingly in the late

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[*] *Remote sensing* designates a variety of activities, from photography to radiometry, conducted from high-flying vehicles and usually measuring electromagnetic radiation reflected or emitted from features on the earth's surface. Mapping by means of aerial photography is a common example, but nonphotographic measurements (photometry) including infrared (heat) and microwave radiation have applications in other areas. Even more useful for some purposes is multispectral sensing, the simultaneous measurement of several different bands in the visible and infrared spectra. A major drawback to surveys by aircraft is the difficulty of covering large areas in a short time. Peter C. Badgley, Leo F. Childs, and William L. Vest, "The Application of Remote Sensing Instruments in Earth Resource Surveys," paper G-23, 35th Annual Meeting of the Society of Exploration Geophysicists, Houston, 6–10 Nov. 1966.

1960s, users of aerial photography and other remote sensing techniques became aware of the potential and limitations of airborne surveys of the earth's surface. Advances in sensor technology had made remote sensing useful in agriculture, forestry, geology and mineral prospecting, oceanography, city planning, and land-use studies. The rise of the environmental movement in the late 1960s brought increased concern for air and water pollution and an appreciation that such problems existed on a scale that could hardly be assessed except through the synoptic eye of the satellite.

Not least important was the realization that the view of earth from an orbiting spacecraft was both wide in coverage and rich in detail. The color photographs taken on early Gemini missions surprised and delighted cartographers and geologists in several federal agencies.[1] Besides having a wide view, a satellite could look at the same site frequently. For some applications, such as crop and snowpack surveys, this kind of real-time data collection exceeded anything aircraft could do.

NASA had launched a series of meteorological satellites (Tiros, Nimbus) starting in the mid-1960s, but in early 1968 was only beginning serious study of other earth-sensing vehicles. Activity in this field was a responsibility of the Manned Spacecraft Center, where remote-sensing instruments were tested on aircraft. By FY 1968 the program had a budget of $6 million and about 150 full-time NASA and contractor personnel assigned. The U.S. Geologic Survey, the Department of Agriculture, and the Naval Oceanographic Office helped to coordinate the program and evaluate its results.[2]

Since crops, minerals, and water supplies were among the features that could be monitored by remote-sensing instruments, the term *earth resources* came to be commonly applied to remote sensing. Toward the end of the 1960s, publicly expressed concern with dwindling natural resources drew much attention, and the notion gained currency that space technology could be exploited to help solve problems on earth. Speaking of this period, a Martin Marietta official later remarked, "Everybody had his own definition of what 'earth resources' meant, but all the definitions were good." Some who viewed the expensive manned spaceflight programs as pointlessly wasteful evidently felt that NASA could redeem itself by contributing to the solution of environmental problems, including resource shortages.[3]

Any such program was bound to have a wider appeal than some of the esoteric science projects. One Skylab program official, commenting on his own experience, said, "When I would [visit my home state] in those days, I could talk about that ATM all day and they'd be polite, but as soon as I started talking about taking a crop survey, my friends . . . knew what that meant." Many congressmen responded similarly. Those who were reluctant supporters of NASA's scientific programs found earth resources a godsend: a space program with a payoff that could be easily appreciated by many of their constituents. The chairmen of both of NASA's House subcommittees became champions of earth-resource experiments. In early 1968, when John Naugle, associate administrator for space science and applications, outlined plans in that area for the Space Sciences Subcommittee, he found congressmen eager to support more than he proposed. At the end of that year the House Subcommittee on NASA Oversight published a staff report urging far more work in the earth-sensing field.[4]

At that time the Office of Space Science and Applications was still studying the objectives for an earth-resources technology satellite and conducting development work on sensors. Naugle told the Subcommittee on Space Science and Applications that he expected to ask for funds in fiscal 1970 to develop hardware for flight in late 1971 or early 1972. Meanwhile, the Office of Manned Space Flight had the only program—Skylab—that might be able to fly sensors any sooner (the official schedule listed an AAP flight in November 1970). Prospects were not good, however, in 1968; after the cancellation of AAP 1A, about all OMSF could do was to establish the requirements for earth-sensing experiments to be carried on some future wet-workshop flight. In a year that saw the solar telescopes come to the verge of cancellation, any thought of adding another major set of experiments was visionary.[5]

Some, however, urged a different course. Jacob Smart, NASA's assistant administrator for DoD and interagency affairs, told George Mueller in May 1968 that an earth-resources project might be the salvation of the space program. "Whether or not justified," Smart said, "earth resource sensing from aircraft and space has been widely advertised as promoting great economic returns." Pointing out the unexpected riches that had been found in the Gemini and Apollo photographs, he suggested that Mueller ask OSSA for suggestions about instruments to fly on Apollo and Apollo Applications missions.[6] Mueller had, in fact, listed earth-resource observations first among several possible objectives for AAP in 1965 (pp. 43–44).

Interest in flying earth sensors on a manned mission remained alive in the Office of Space Science and Applications, though tempered by the experience with AAP 1A. When Floyd Thompson's Post-Apollo Advisory Group (pp. 97–98) suggested earth sensing as a promising activity for manned spaceflight, OSSA once again looked into the possibilities. If OMSF could orbit a substantial earth-sensing payload in 1969 or 1970, it could provide useful data for designing the earth-resources technology satellite, still in the planning stages. The Thompson committee's report, however, was not too promising, according to one OSSA official who looked into it. Coverage of the United States from the proposed wet workshop was negligible on account of the low orbital inclination* obtainable with a Saturn IB. The committee's estimate of the cost of such a mission was much too low. And finally, unless the experiments were defined as primary objectives of the flight, they would likely be dropped when schedules and budgets got tight—as they inevitably would (witness AAP 1A). It was simply not prudent for OSSA to rely on manned programs to provide information, though of course the possibility should not be excluded.[7]

One more influential voice was added to the chorus calling for earth-resource missions when the National Academy of Sciences published a report summarizing a two-year study of applications satellites conducted for NASA. That report urged a two- to three-fold increase in funding for applications satellites, more attention to communications and navigation vehicles, and a pilot program for an earth-resources satellite.[8]

In view of the ready market for earth-surveying experiments that existed in early 1969, it would have been surprising had the Office of Manned Space Flight *not* revived its earth-resource experiments—which it did. By the fall of that year, when the dust had settled somewhat after the dry-workshop decision, meetings were being held to determine whether the AAP 1A sensors, or upgraded versions of them, could be accommodated on the workshop. The Office of Space Science and Applications was defining a package of such experiments for study by its Space Science and Applications Steering Committee.[9]

EARTH-RESOURCE EXPERIMENTS

When preliminary studies showed no insurmountable problems, MSC quickly presented a proposal to the Manned Space Flight Experiments Board on 8 December 1969. Leonard Jaffe, who as acting director of the Earth Observations Program Division represented OSSA, was concerned by the hasty preparation of the proposal. He noted several important unresolved questions—cost, particularly, but also the state of definition of the sensors themselves. Still, Jaffe strongly supported flying such a set of experiments and said that OSSA would present some definitive recommendations as soon as possible. Charles Mathews, chairing the meeting, conceded that funding and management needed more study; but he, too, strongly favored the project. The board accordingly gave final approval to only one of the proposed experiments, deferring consideration of the rest until better information was available.[10]

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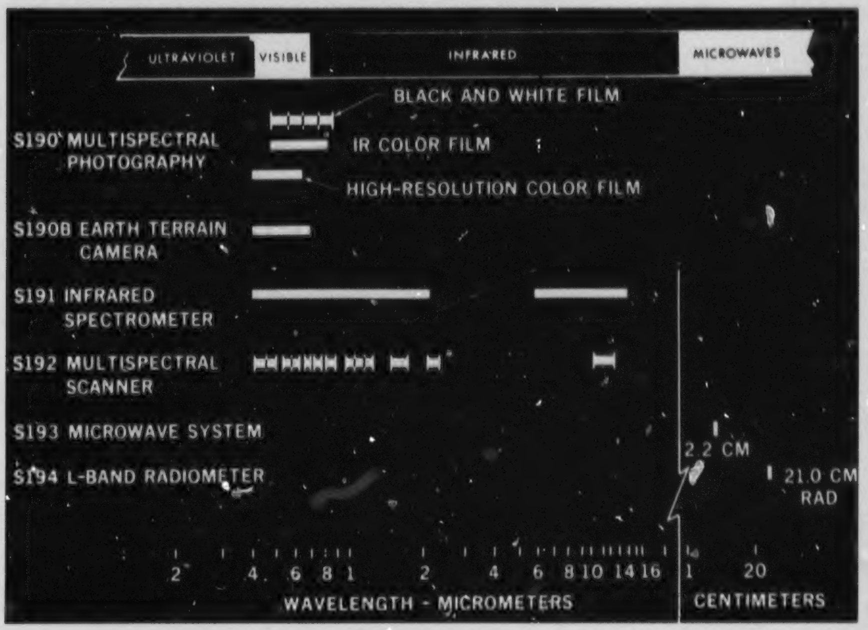
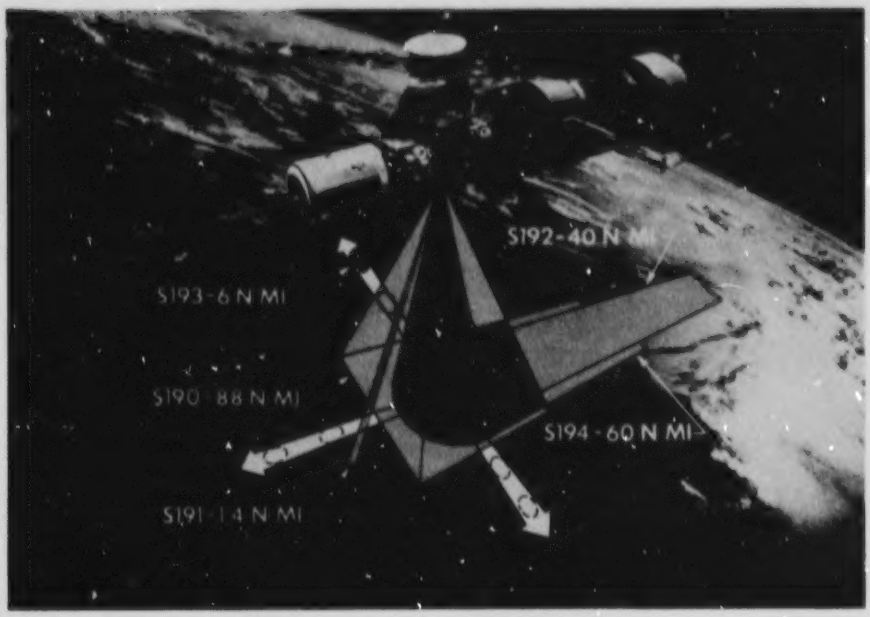
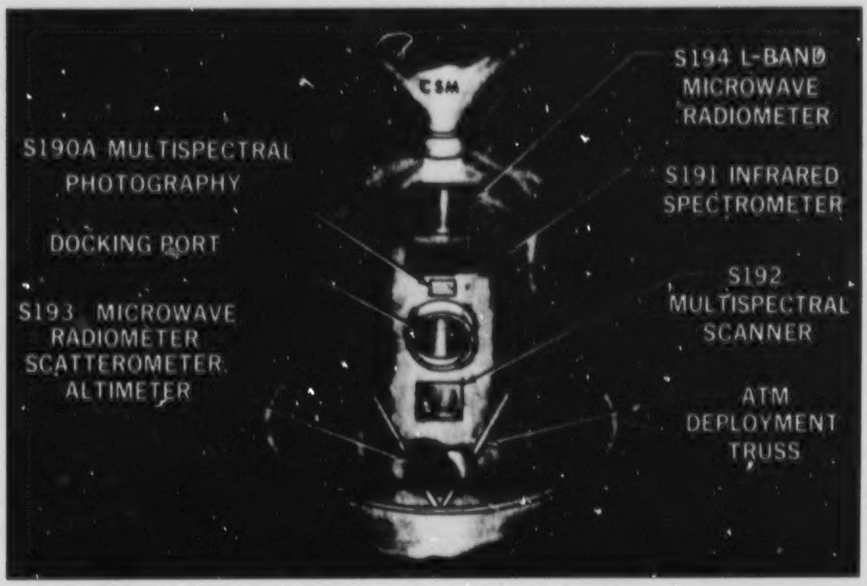
* The angle of the orbital plane with the equator, e.g. 30°, gives the latitudes that mark the northern- and southern-most travel of the spacecraft. At an inclination of 30°, about as high as the wet workshop could go, the spacecraft flies no farther north than New Orleans.

Initially four instruments made up the new earth-resource experiments package. The only one that had been flown before was the multispectral photographic facility (experiment S190A; all experiments are listed in app. D). This was an improved version of an experiment flown with great success on *Apollo 9* the previous spring. It consisted of six precision cameras with carefully matched lenses, each using a different film and filter combination to record a different spectral range of visible or infrared light. The other instruments, all experimental in the sense that their use in orbit had not been proved, were radiometric rather than photographic; they recorded the intensity of radiation emitted by or reflected from surface features. Two of these, a spectrometer (S191) and a 10-band multispectral scanner (S192), operated in the infrared. The spectrometer recorded the wavelength and intensity of infrared radiation from selected small areas (0.45-kilometer diameter) on the ground; the multispectral scanner simultaneously measured the intensity of infrared in 10 wavelength ranges, scanning a swath 74 kilometers wide centered on the spacecraft's ground track. The fourth instrument (S193) had two functions: it was a microwave radiometer, similar to the infrared instrument but sensing longer wavelengths, and a radar scatterometer, which measured the reflective properties of the surface toward radar waves. Somewhat later two more instruments were added: a passive L-band radiometer, S194, to map temperatures of terrestrial surfaces; and a higher-resolution camera, S190B, to aid in interpretation of data from the other sensors.[11]




S192-40 N MI
S193-6 N MI
S190-88 N MI
S194-60 N MI
S191-1.4 N MI

Earth-resource experiments, as depicted on briefing charts. Above, area coverage of the first five instruments. S190B, added later, photographed a 109-km (59-nm) square. S-71-2255-S. *Left, the frequency coverage of all six instruments.* S-72-216-S. *Below, the bottom of the docking adapter, showing the sensors of the first five instruments. S190B was designed to be operated through the scientific airlock in the workshop.* S-72-214-S.


CSM
S194 L-BAND MICROWAVE RADIOMETER
S190A MULTISPECTRAL PHOTOGRAPHY
S191 INFRARED SPECTROMETER
DOCKING PORT
S192 MULTISPECTRAL SCANNER
S193 MICROWAVE RADIOMETER SCATTEROMETER ALTIMETER
ATM DEPLOYMENT TRUSS

Skylab Program Director Bill Schneider immediately ordered the centers to begin preliminary work: MSC to prepare the documentation, Marshall to study integration requirements and hardware modifications, and all three centers to continue basic compatibility studies. Every effort had to be made to keep costs down. The experiments board had been given an estimate of $10 million for developing the instruments and $11.125 million for support and data analysis, the latter to be funded by OSSA and user agencies.[12]

Early in February OSSA recommended that the first four instruments be flown; Dale Myers agreed on the 16th. The microwave instrument was only provisionally approved, however, since its compatibility with the spacecraft had not been conclusively established and it might cost an additional $2 million. Directing the centers to proceed with the earth-resource experiments, Schneider reminded them that "all possible effort must be made to deliver [the experiments] within present cost and schedule guidelines"—that is, $25 million for development, integration, and delivery by July 1971. Should development costs exceed the budget, it would be necessary to consider dropping the entire package. Requests for proposals were sent out, a source evaluation board appointed, and by the middle of 1970 contracts had been awarded for the instruments.[13]

Schneider's correspondence for the next six months documented a steady increase in projected costs, along with his repeated warnings that "we have no resource reserves to cover additional requirements." By mid-March the cost of the multispectral cameras was twice what had been estimated in December. By June, the cost of the entire package had soared to $36 million, and Schneider warned that reconsideration might be necessary. In June, although the Skylab office recommended deleting the microwave sensor, the Manned Space Flight Experiment Board, persuaded by OSSA's pleas to keep it, urged developing all the instruments for flight.[14]

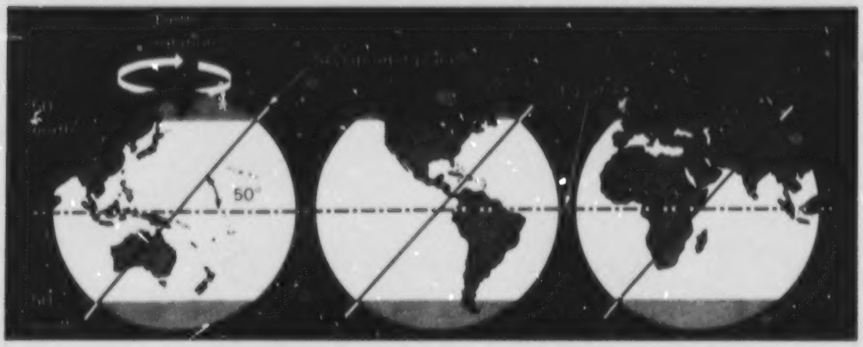
Despite a cut in NASA's overall budget that summer, Myers had little choice but to go ahead with the earth-resource instruments. He informed Administrator James Fletcher of this intent in July, saying that he was limiting the cost of the project to $36.4 million. The extra $11.4 million would come from "further reduction in the planned Skylab uncosted obligation at the end of FY 1971"—in other words, out of funds already allotted for Skylab. Schneider passed the word to the center program managers, directing them to reallocate funds within current fiscal limitations. From Houston, where much of the burden of cost reduction would fall, Kenneth Kleinknecht told Headquarters that his back was to the wall, financially, and that the other projects in Skylab might suffer. He added that Washington ought to consider the centers' problems before adding expensive new experiments to a maturing program.[15]

Six months later costs had gone up still more, to an estimated $42 million, but seemed to be under better control. In mid-1971, reviewing the project's cost history for Myers, Schneider attributed much of the trouble to unrealistic initial estimates and to less-than-effective management at all levels. The fact that the sensors had been flown in the aircraft program—which was only approximately true—had thrown managers off their guard and led to poor assessment of development problems and costs. In the general eagerness to get the package ready for flight, neither OSSA nor OMSF had formulated requirements in sufficient detail before soliciting bids; changes in specifications during contract negotiation had increased costs. Nor had there been adequate coordination between MSC's Science and Applications Directorate (which directed instrument development) and program control officials in the Houston Skylab office. Changes had been made in the experiments without full assessment of the consequences. In sum, it had not been a good job of management, and in their haste to get the instruments into the program, managers at all levels had proceeded less carefully than they should have. The project was now under control, but any new major problems could wreck it.[16]

Looking for a place to put the instruments and their control systems, planners quickly settled on the multiple docking adapter, where space was still available. An optical-quality window would have to be added for the multispectral cameras; the infrared spectrometer would have to be installed through the pressure hull; and brackets would have to be added to the outside to support the microwave and multispectral scanners, both of which used large antennas. Marshall went ahead at once with these changes, though they caused some interference with systems already installed on the module.

The requirements of the earth-resource experiments caused major changes to mission plans. Primary among these was an increase in orbital inclination to 50°. *Skylab* would now go as far north as Vancouver, Winnipeg, Bastogne, Frankfurt am Main, Kharkov, Mongolia, and Sakhalin Island north of Japan. To the south, *Skylab* would pass over all of Australia and Africa and most of South America, except Tierra del

Skylab*'s area of operations with 50° orbital inclination*. S-72-1795-S.



Fuego. Three-fourths of the earth's surface would lie under *Skylab*'s path, the area where 90% of its population lives and 80% of its food is produced.[17]

Since NASA's network of tracking and communications stations was sited to cover a spacecraft in an orbit of lower inclination (or on its way to the moon), the 50° orbit meant that *Skylab* would be out of contact during a large fraction of each orbit. The increased inclination also changed the angular relation of the orbital plane to the sun line, requiring recalculation of heat loads in the workshop and power production by the solar arrays.[18]

Among the more significant changes was the new orbital attitude required by the earth-sensing experiments. While the solar telescopes had to be pointed directly at the sun, the earth sensors had to be aimed at that point on the earth's surface directly beneath the spacecraft (nadir). Except for minor perturbations, inertia would keep the cluster aligned with the sun, but would move it continually with respect to the nadir. When the earth-resource experiments were operating, the spacecraft would have to rotate at an angular rate equal to its angular velocity in orbit, about 4° per minute. This mode of operation (called the Z-local vertical because the Z axis of the orbital assembly pointed toward the center of the earth at each instant) made solar observations impossible, changed the cluster's heat balance, and reduced power production.

The new requirements, plus increasing weights and moments of inertia in the workshop cluster, touched off a series of design changes in the attitude-control system. Whereas the control moment gyros had been responsible for attitude control during solar observations and the thruster system was to be used for other maneuvers, Marshall engineers now transferred most of the maneuvering responsibilities to the gyros, with the thrusters held in reserve. New control programs were entered into the ATM's digital computer, which could, on command from the control and display console, maneuver the cluster between solar inertial and Z-local vertical attitudes and into any of several other attitudes required in special circumstances.[19]

The earth-resources package presented its largest challenge to flight planners. The photographic instruments required specific lighting conditions, which restricted the number of sites* that could be photographed from *Skylab*'s orbit. Thermal and power problems in the Z-local-vertical attitude limited the number of successive earth-observing passes. Except for the microwave sensor, the earth-resource experiments were limited by weather conditions at the surface; observations planned for one pass might have to be postponed if cloud cover was heavy. And always there was the fact that time for the earth-resource observations would have to be taken from medical or solar experiments or both.

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* Since much of *Skylab*'s flight path was over foreign countries, some of them sensitive to the possibility of surveillance from orbit, the use of the word *target* to refer to ground sites was forbidden. The word was not used even in training, lest an astronaut inadvertently use it in flight. Leonard Jaffe to Skylab prog. dir., "Nomenclature for EREP Observations," 31 Aug. 1972.

In view of these limitations, a preliminary study showed that about 45 of *Skylab*'s trips across the United States during the three missions would be useful for earth-resource sensing. That figure was used for planning purposes for about a year, until proposals from potential users demanded more. It would take a great deal of juggling to optimize all the factors that had to be taken into account.[20]

SELECTING THE INVESTIGATORS

For two years, no one knew exactly what the earth-resource instruments were going to do. Not only was NASA evaluating a set of sensors; it was also evaluating a new concept of experiment management. The earth-resource instruments were to be a scientific "facility," whose specifications were determined by NASA; users would be asked to propose specific uses for the data those instruments could gather. (Previously experimenters had proposed both the instrument and the experiment, with NASA providing support for its development and the spacecraft on which to fly it.) The principal investigators' responsibilities for earth resources were not the same as those of the principal investigators for the solar telescopes. Users would have no control over sensor design, but they could (within operational limits) specify when and where they wanted data taken.[21]

Until those users were chosen, a number of important activities could not proceed. Particularly frustrated by this situation was Eugene Kranz, chief of Houston's Flight Control Division. Having to define its role in Skylab by the end of 1970, Kranz's division could not get a grip on the earth-resources package. Whereas normally the office would have sponsored meetings with experimenters to find out what they needed from the instruments, there were—only two years before flight—no investigators to talk to. Nor could requirements be compared effectively with the design constraints of the cluster during critical design reviews. In mid-1970, Flight Control had been given responsibility for collecting Skylab's data requirements, including data processing and distribution, and once more the earth-resource experiments raised unanswerable questions. Was the purpose of the experiments to evaluate the sensors or to collect data? The distinction markedly affected the way experiments would be handled. Pending receipt of specific instructions, Kranz decided to treat the earth resources as data-collecting science experiments. He was aware that this conflicted with other opinion at MSC, but by taking that approach he hoped to get some clarification of center policy.[22]

Kranz's difficulty undoubtedly stemmed from the same source as Schneider's cost problems: the haste with which NASA was attempting to organize and carry out a major addition to an existing program. With OSSA in charge of some aspects of earth resources, MSC responsible for others,* and Headquarters coordinating the activity under severe budgetary restraints, it is probably not surprising that communication sometimes broke down.

Even as Kranz was complaining, however, selection of experimenters was about to begin. On 22 December 1970, 6000 announcements of flight opportunity were sent out to potential users of earth-resource data. Universities, state and local government agencies, private concerns, and foreign governments were solicited for proposals. By mid-1971 approximately 230 proposals had been received and screening had begun. After the Office of Space Science and Applications had examined them for scientific merit, the proposals were evaluated by the manned spaceflight centers (primarily MSC) for compatibility with the planned missions. Not until that process was complete could definitive flight planning begin.[23]

Although many proposals needed to be better defined, there were more good proposals than 45 earth-resource passes allowed for. Schneider therefore directed Houston and Huntsville to determine how much more Z-local-vertical time they could provide. Marshall found that within certain limitations, another 40 passes could be made; the main problems were encroachment on ATM observing time and providing space to store film. The extra 40 passes included some in the solar inertial attitude; for some investigators an oblique view of the earth was acceptable, and this allowed the earth sensors and the solar telescopes to operate simultaneously. With these extra passes available, 160 of the more than 230 proposals were placed on a candidate list for further negotiation.[24]

Consultation with the investigators during the first half of 1972 produced changes to many of the proposals and brought them within Skylab's capability. As MSC got a clearer picture of the cost of supporting these investigations, however, officials urged cutting the total to a far smaller number—a proposal vigorously opposed by both OSSA and OMSF. When Headquarters suggested that management of some of the investigations could be moved elsewhere to relieve the strain on MSC, the center agreed to negotiate with all 160. In August 1972, nine months before the scheduled flight of the first mission, Headquarters announced that 106 investigators, 83 from the U.S. and 23 from other countries, had been selected for the earth-resource experiments.[25]

FLIGHT PLANNING AND INSTRUMENT DEVELOPMENT

While project officials were negotiating the final details of earth-resource experiments with investigators, mission planners were refining

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*In 1970 as in 1967, MSC was wrestling with Apollo problems—not a catastrophe this time, but a near miss: the aborted flight of *Apollo 13* in April 1970 and the subsequent investigation.

their plans for taking data. An important change was made early in 1972, when Houston proposed to launch the workshop into a controlled repeating orbit, in which the spacecraft passed over the same point at regular intervals, to increase the probability of successful coverage of the earth-resource sites. With Marshall's concurrence, this feature was incorporated into mission plans in June. The workshop was to be inserted into a 372.5-kilometer orbit that would repeat its first ground track on the 72d revolution, five days (less two hours) later. Minor adjustments would be made periodically during the mission to correct for normal perturbations.[26]

Flight planning for earth-resource passes was at least as complex as any other experiment activity in Skylab, including the solar observations. There were 570 combinations of ground sites and experimental tasks to be accomplished in 60 earth-oriented passes during the three missions; frequently ground observations or aircraft flights had to be coordinated with orbital passes, to calibrate the instruments. Weather conditions could always interfere. And after completing an observing pass, experimenters could never be sure that they had secured the data they wanted, since results were not available until the film was processed on earth after the mission.

Mission planners worked out basic earth-resource procedures in the first half of 1972. Planning for a given day's observations would start five days before (a consideration based on the five-day repeating ground track), with all of the activities preplanned for the mission but not yet accomplished put on a "shopping list." Many of these would be eliminated because of the spacecraft's ground track or the crew's work-rest cycle. Those remaining would be compared against the expected sun angle, the day's flight plan (other experiments might have higher priority), and the condition of the workshop's attitude-control system. Weather forecasts and the readiness of ground support and aircraft were then considered, perhaps eliminating a few more possible activities. Two days before execution, planners chose the observations with the highest probability of success, and summary flight planning began, with updated weather forecasts being continually monitored. On the day before, detailed flight planning was completed—coordinates of each site, instruments to be operated, time of spacecraft maneuvers—and, after checking the latest available weather reports, flight planners committed *Skylab* to an activity not later than three hours (two orbits) before it was executed.[27]

The short time available for development of the instruments presented problems. While the S190A cameras were similar to others that had been flown before, the infrared and microwave sensors were less well developed and encountered a number of delays. Martin Marietta, whose responsibility included both integrating the experiments into the multiple docking adapter and building the controls and displays for them, often had to cope with changes in the instruments that affected the company's own hardware. To make sure that everyone concerned was aware of the implications of such changes, Martin set up a working group of representatives of the five other contractors and the astronaut office, which met monthly to make decisions on proposed changes. It was probably the only way that the tradeoffs between the various factions could be accomplished in the time available.[28]

By November 1971, Program Director Bill Schneider could report to the Office of Space Science and Applications that flight hardware had been completed and delivered for integration into the multiple docking adapter. In spite of that, each sensor had one or more problems that would require hardware changes before launch; and after integration checks the instruments were pulled off the module for additional work. Some subsequent qualification tests required juggling the schedules to work around the missing experiments.[29]

Late in 1971 Schneider again recommended cancellation of two experiments. The multispectral scanner was experiencing difficulties that could delay launch, and the microwave sensor had so few investigators interested in its data that it seemed an unjustifiable expense. Neither experiment was in fact dropped, but OSSA conceded that the multispectral scanner was expendable if the workshop launch had to be postponed on its account. Any lengthy delay would disrupt the seasonal variations that other investigators wanted to observe, and the multispectral scanner was not worth that.[30]

On 6 October 1972 the multiple docking adapter and airlock were delivered to the Cape. The S193 microwave experiment arrived nine days later. During the next few months a number of equipment failures occurred; both the multispectral scanner and the microwave sensor had to be returned to the manufacturers for correction of defects, as did the control and display panel and one of the tape recorders. Late in March 1973 the last earth-resources simulation test was completed satisfactorily, and the experiments were pronounced ready to go.[31]

STUDENT EXPERIMENTS

While the earth-resource experiments were publicized as offering benefits to the public as a whole—in contrast to the medical and solar astronomy experiments—some in the Skylab program felt that public interest and support should be broadened. In the spring of 1971 Ken Timmons, a Martin Marietta official whose office had responsibility for the multiple docking adapter, conceived the idea of allowing high-school students to propose some simple experiments for the workshop. Preliminary discussions with Colorado education officials indicated a strong interest, so Timmons passed the idea on to Marshall Space Flight Center. Skylab manager Leland Belew also liked the idea, and he in turn mentioned it to William Schneider in a telephone conversation. Headquarters then negotiated a contract with the National Science Teachers Association to organize and manage a nationwide competition for student proposals.[32]

In October 1971 NSTA mailed out some 100 000 announcements, specifying a 4 February 1972 deadline for receipt of proposals. More than 55 000 teachers requested entry materials and 3409 proposals were finally submitted, involving over 4000 students from all 50 states in grades 9 through 12. By 1 March, 12 regional screening committees had selected 300 proposals for the final winnowing, which would produce 25 winners. Proposals were judged by NSTA on scientific merit, but throughout the selection process NASA engineers were called on for quick judgments as to feasibility. By 15 March, 25 national winners and 22 "special mention" entries had been chosen.[33]

The selection process had taken into account such limitations as weight, volume, power consumption, and crew time needed. But once the winning experiments had been chosen it was necessary to run them through NASA's normal sequence of reviews. To avoid overwhelming the students with paperwork, however, certain documentation requirements were relaxed; a streamlined system of record-keeping summarized the results of the reviews. And in light of the short time available for developing the experiments, project officials insisted that each NASA office designate a single person to participate in reviews. This ensured that action could be taken on the student experiments when necessary.[34]

The 25 winning students participated in a preliminary design review at Huntsville during the week of 8 May 1972. The experiments were put into three categories: those that required fabrication of separate pieces of hardware, those that could be affiliated with existing Skylab experiments, and those whose general objectives could be attained by cooperation with related research already in the program. Six experiments were put in this latter category when it developed that they could not be carried out on account of technical problems. These students were allowed to work with principal investigators whose research programs closely approximated their own interests, so that they could at least participate in some part of Skylab's science program. Of the rest, 8 would use data already planned for collection and 11 required development of new hardware. These students spent the next three months working with NASA advisers, designing the equipment for their investigations and preparing for a critical design review in August. By early 1973 the student experiments had been completed. The flight acceptance review was held at Marshall 23–24 January and flight units were delivered to the Cape two days later.[35]

The experiments devised by these students ranged in quality from fair to extremely good, according to Marshall's program manager and others who participated in the judging. One proposal called for measuring the intensity of neutron radiation at orbital altitudes, something that professional scientists had never done. Another proposed to study x-radiation from Jupiter, using one of the ATM instruments. One of the most widely publicized student experiments was designed to study adaptation to zero g by determining whether a spider could spin a normal web and, if not, whether the arachnid could adapt to weightlessness during a mission. Others dealt with questions in astronomy, biology, and space physics (all 19 are listed in app. D).

Both NASA and NSTA participants were agreeably surprised by the overall sophistication of the student proposals. Some of the students, on the other hand, felt that NASA's expectations had been too low. One significant secondary finding was that many students had serious misconceptions of scientific principles and the scientific method, leading some of the evaluators to examine their own college-level teaching. The contest judges were also distressed to find that quite a number of the students could not express themselves clearly in writing.[36]

The student experiments were the last addition to Skylab. On the whole, it was probably a worthwhile exercise. Both students and science teachers were grateful for NASA's interest in science at a preprofessional level. The student winners, though few in number, learned a great deal—not only about science, but about the day-to-day conduct of a complex project like Skylab, where nonscientific considerations often determine the course of a scientific project.

11

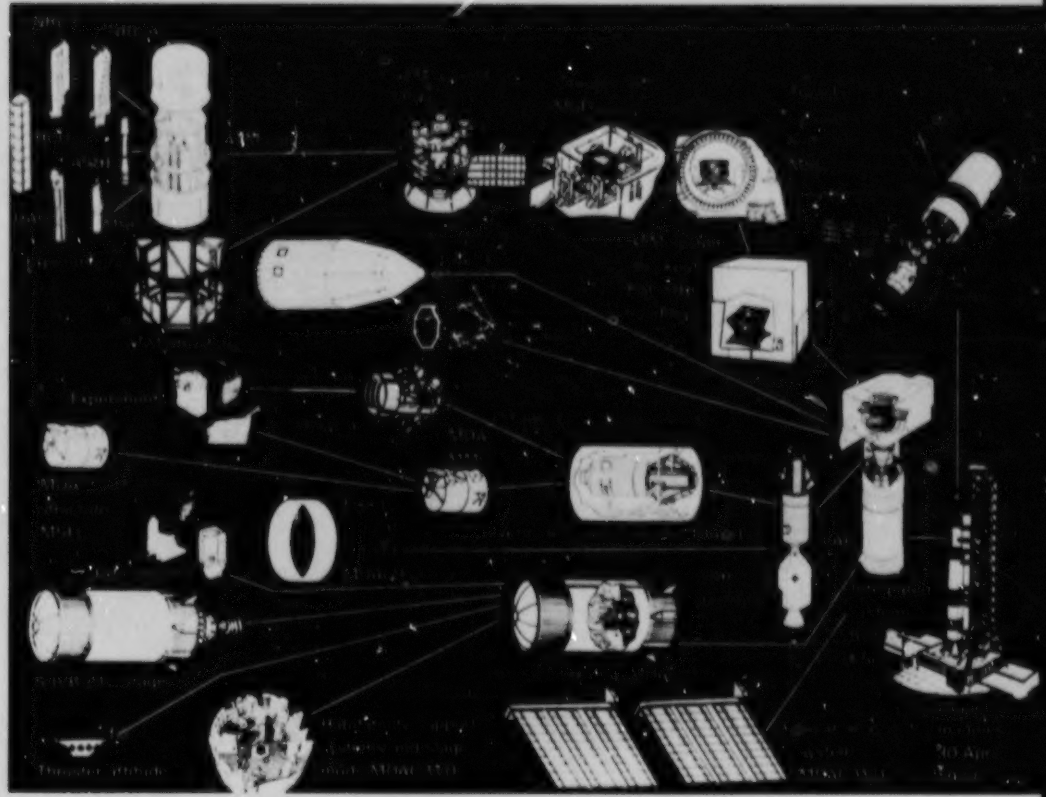
Putting the Pieces Together

In the year following July 1969, Skylab program managers and engineers adjusted their plans to the new capabilities of the Saturn V dry workshop. Initially changes were limited, by Headquarters order, to those made necessary by the wet-to-dry conversion; but many improvements and additions were soon authorized. By July 1970 most of these new features had been assimilated; a program review reaffirmed Skylab's schedule and budget, marking the end of major design refinements (pp. 125–27, 144–48). Later that summer, critical design reviews on the three major cluster modules put further changes under the jurisdiction of configuration control boards. Thenceforth only deficiencies discovered during testing could justify major modifications.

More Work for Contractors

Comparing resources to the dry workshop's new requirements in August 1969, Marshall's program office determined that some of the required changes could not be accomplished at the center. The new support and deployment structure for the Apollo telescope mount, for example, would overtax Marshall's shops, which were already building the mount and the multiple docking adapter. Instead, Marshall proposed to add the new structure, along with the shroud that protected *Skylab* until it reached orbit, to McDonnell Douglas's contract for the airlock. Similarly it was apparent that equipping and checking out the multiple docking adapter, about to become the control center for both the solar observatory and the new earth-resource experiments, exceeded Marshall's capacity. Accordingly, Huntsville's managers decided to add to an existing contract with the Martin Marietta Corporation the responsibility for outfitting the docking adapter.[1]

Martin Marietta had held a contract for payload integration since AAP's early days, when the program consisted of many small payloads each carrying a set of related experiments. Under this concept, the com-



Movement and assembly of hardware for Skylab. Abbreviations: AS&E, American Science & Engineering; ATM, Apollo telescope mount; HAO, High Altitude Observatory; HCO, Harvard College Observatory; KSC, Kennedy Space Center; MDA, multiple docking adapter; MDAC-ED, McDonnell Douglas Astronautics–Eastern Div.; MDAC-WD, Western Div.; MMC, Martin Marietta Corp.; MSC, Manned Spacecraft Center; MSFC, Marshall Space Flight Center; NRL, Naval Research Laboratory; O&C, Operations & Checkout Bldg.; VAB, Vehicle Assembly Bldg. PM-7200-135.

pany was responsible for seeing that mission payloads were compatible, qualified for spaceflight, and suitable for accomplishing mission objectives. It was a broad responsibility, encompassing mission planning, operations, and training, as well as hardware procurement. As AAP shrank, however, during 1967 and 1968, Martin's responsibilities dwindled; NASA program offices had trouble finding appropriate work for the company's engineers to do. Martin was not happy with this situation, and company officials were particularly disappointed when AAP mission 1A was canceled (pp. 87–88). Early in 1969, Marshall redefined Martin

Marietta's duties in Apollo Applications and definitized the firm's letter contract. Under the new arrangement Martin would conduct specific engineering studies in support of integration decisions made by the NASA centers: electrical power and thermal analyses, experiment compatibility studies, coordination of test plans, and mission planning. In addition, the contractor would assist NASA by keeping track of configuration changes, updating the interface specifications and interface control documents, and maintaining the document repository at Huntsville.[2]

Assignment of the multiple docking adapter to Martin Marietta's Denver Division was both logical and helpful to the company. Completing the adapter was fundamentally a job of integration, which was Martin's acknowledged task; but as long as the company had no hardware responsibilities, its relation to the other prime contractors had been somewhat ill-defined. While the integration contractor had provided much necessary information, it was NASA and the prime contractors who had made the integration decisions. The docking adapter, which connected to all the other cluster modules, put Martin on an equal footing with the other major contractors.[3]

TEST PROGRAM

Since *Skylab* was one of a kind, there would be no preliminary flights to discover and correct design deficiencies; preflight testing assumed critical importance early in the program. While some components of the cluster—the S-IVB stage, for example—were either well proven items or sufficiently similar to Apollo hardware that exhaustive testing was not required, many others were untried. Each new component had to be qualified during development. A carefully documented test program was formulated and followed, to ensure that every part would survive the stresses of launch and function as required under mission conditions for its specified lifetime.

Two primary documents defined the test program. The mission requirements document specified exactly what each mission was to accomplish; and the cluster requirements specification defined permissible materials, design and construction practices, and human engineering standards. From these documents, NASA test engineers developed the procedures for contractors to follow in order to satisfy the agency that hardware would be acceptable.[4]

There were two main phases in the overall test program: development tests, used by contractors to work out the best choice of materials and designs, and qualification tests to demonstrate that a component was adequate for its intended function. For the first phase, design-verification test units were built that did not have to conform fully to flight specifications. When Marshall built the medical experiments, for example, design-verification test units enabled engineers to work out such things as the optimum size for the bicycle ergometer and the lower-body negative-pressure device, the range of adjustment necessary to accommodate the crewmen, and the electronic circuitry necessary to transmit medical data to the experiment support system. After the design was acceptably verified, a qualification unit, identical in all respects to the flight hardware, was fabricated and subjected to all necessary tests. Following the qualification tests, several of the test articles were refurbished and converted to training units or backup hardware.[5]

Since almost everything on *Skylab* functioned as a part of a larger system, compatibility was as important as reliability. As assembly proceeded, systems tests were conducted at progressively higher levels of complexity to discover and correct any mechanical, electrical, or electromagnetic incompatibilities. In principle, systems testing should have continued all the way through verification of the entire cluster with all its systems operating; in practice, this could not be done. It was impractical, for example, to test the jettisoning of the payload shroud, the deployment of the Apollo telescope mount, or the unfolding of the solar arrays on the workshop and telescope mount. Each of these operations, however, was verified by analysis, testing with nonflight hardware, and simulations.[6]

Because of the complexity of the modules and the number of tests they went through, program officials decided at the outset to set up a test team, composed of contractor and agency engineers, for each of the major modules. From contractors' plants to Houston, Huntsville, and Cape Canaveral, these teams went with their modules to each test site, assisting resident personnel in post-acceptance testing. The experience thus accumulated was of great value in trouble-shooting and correcting test anomalies as they were encountered.[7]

MODULE DEVELOPMENT: AIRLOCK AND DOCKING ADAPTER

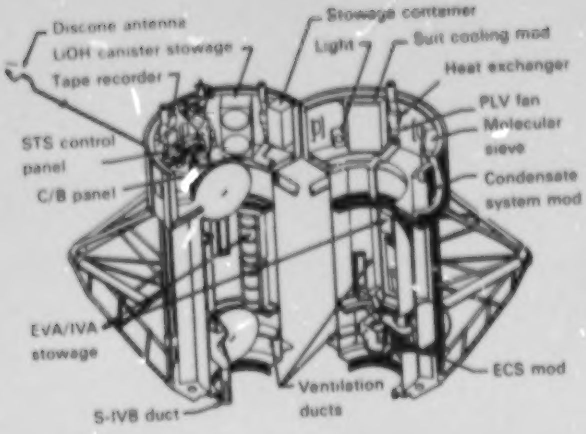
Although the airlock and the multiple docking adapter were separate entities built by different contractors, they were in many respects simply two components of a single module. (When the adapter had first been proposed, in fact, Houston—then in charge of the airlock—had refused to consider it as anything but an extension of the airlock.) Production plans called for the two units to be joined and tested as a single unit before being shipped to KSC. Martin Marietta and McDonnell Douglas's Eastern Division at St. Louis thus became close collaborators.

By July 1969, airlock and adapter had gone through considerable evolution. The airlock, which in 1965 had been a rather simple tunnel giving access to the S-IVB tank and to the outside, had grown much more complex as program concepts matured. Besides its airlock function, in the dry workshop it carried the cluster's communications, electrical power distribution, and environmental control systems. A new structural transition section, 3.05 meters in diameter and 1.2 meters long, provided space for the control panels and equipment as well as the base for attachment of the multiple docking adapter. The airlock's structural trusses carried cylinders of compressed gases for the workshop atmosphere. With the change to the dry workshop a fixed airlock shroud, of the same diameter as the S-IVB, was added to serve as the base on which the Apollo telescope mount deployment structure stood. During four years of change, the airlock's launch weight had grown from about 3600 kg to nearly 35 000 kg.[8]

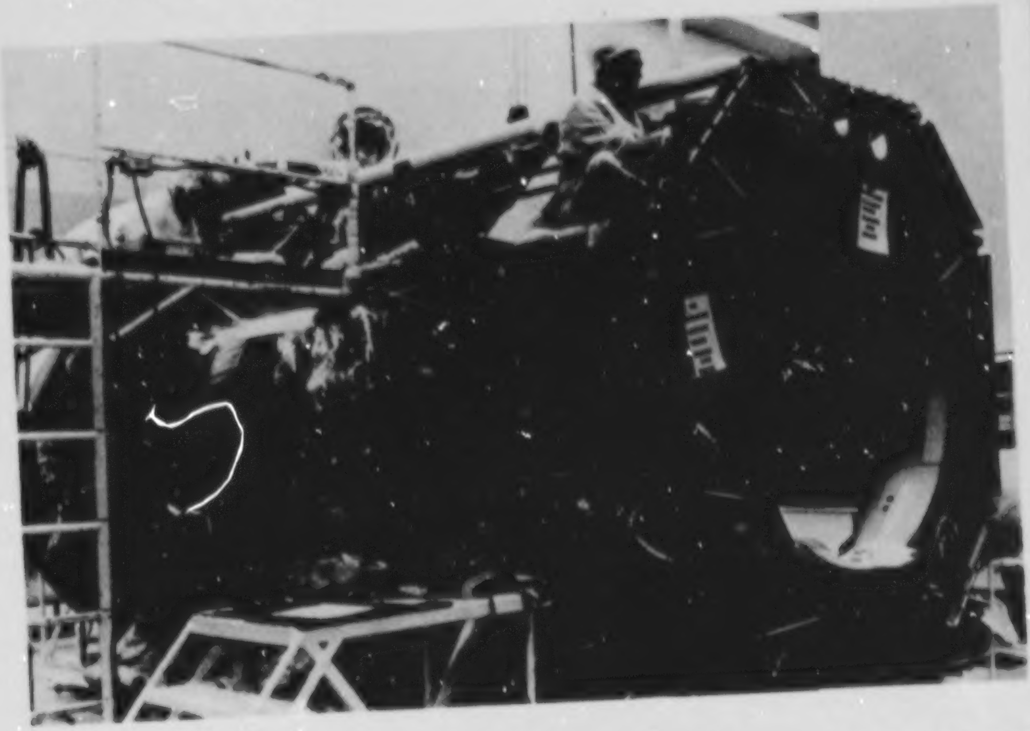
Similarly, the multiple docking adapter was no longer a simple passive module enabling the cluster to carry several experiment packages. During 1967 and 1968 it had been enlarged to provide space for carrying the workshop's furnishings into orbit, meanwhile losing one after another of the original five docking ports. The dry-workshop decision, however, nullified this function, and at mid-1969 the adapter was once again a virtually empty shell: a cylinder 3.05 meters in diameter by 5.25 meters long, with the main docking port in its forward end and a contingency port on one side, enclosing about 35 cubic meters of space. Some of this space was immediately preempted for the Apollo telescope mount's control and display panel; within a short time more of it would be taken up by the earth-resource experiments and their supporting equipment. Not surprisingly, the adapter became, in the latter stages of the program, a kind of catch-all for equipment storage and work space. This led to a somewhat random arrangement of crew stations within the adapter, making it quite a different environment from the workshop with its predominant one-g orientation. The difference was the subject of considerable comment by the crews, but no one found it distracting.[9]

During 1970 and 1971 much of the development testing for the airlock and adapter was conducted. Static tests at Huntsville subjected the test articles to the structural loads expected to be imposed at launch. Internal pressurization and leakage tests verified the integrity of hatches and seals under prelaunch and orbital conditions. Meanwhile, at NASA's Plum Brook Station in Ohio contractor and NASA engineers were verifying the systems for jettisoning the payload shroud. Three separate tests of the explosive system for separating the shroud into four segments were successful, with only minor discrepancies requiring attention. Completion of these two sets of tests cleared the way for the next stage of cluster testing.[10]

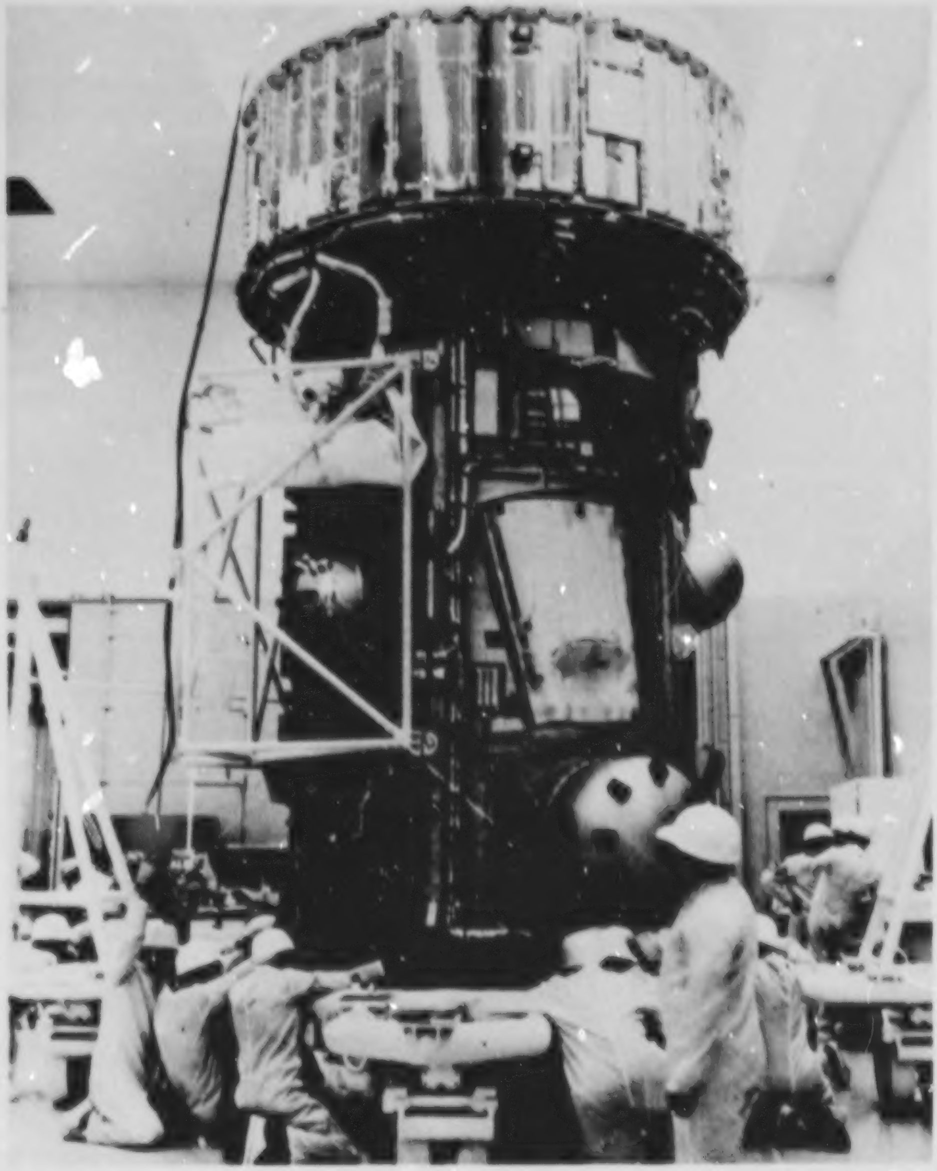
The last major development tests on the cluster modules came in 1971 and 1972, when high-fidelity mockups were put through vibroacoustic tests at Houston. Subjecting the modules to the vibration and sound pressure expected during powered flight had two objectives: to determine that the structures could withstand the environment and to find out whether the criteria set for qualification tests were adequate. The


Discone antenna
LiOH canister stowage
Tape recorder
STS control panel
C/B panel
EVA/IVA stowage
S-IVB duct
Stowage container
Light
Suit cooling mod
Heat exchanger
PLV fan
Molecular sieve
Condensate system mod
ECS mod
Ventilation ducts

The airlock module in January 1968, left, S-68-604, and under construction at McDonnell Douglas Astronautics Co. in St. Louis in 1971, below, ML71-7322, *and in 1972, right,* 72-H-86.

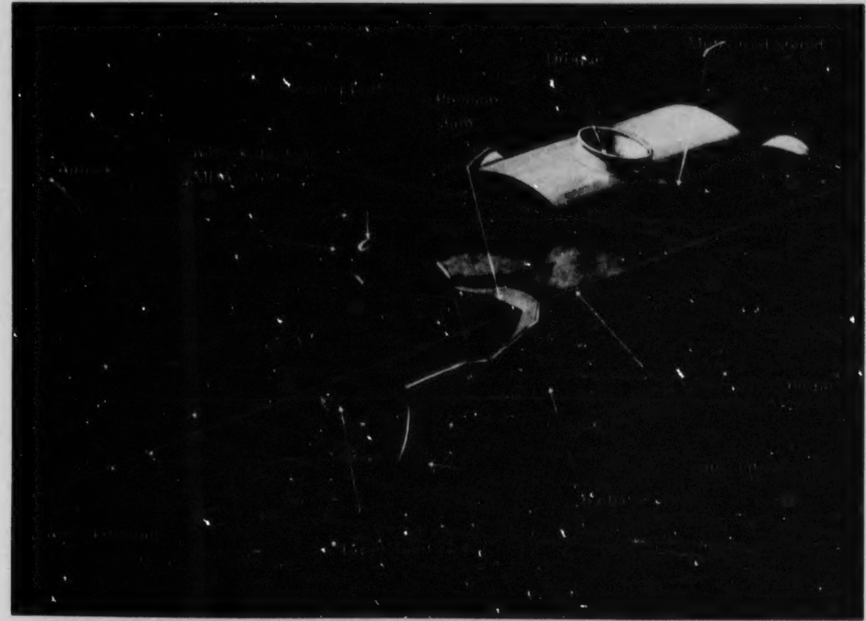


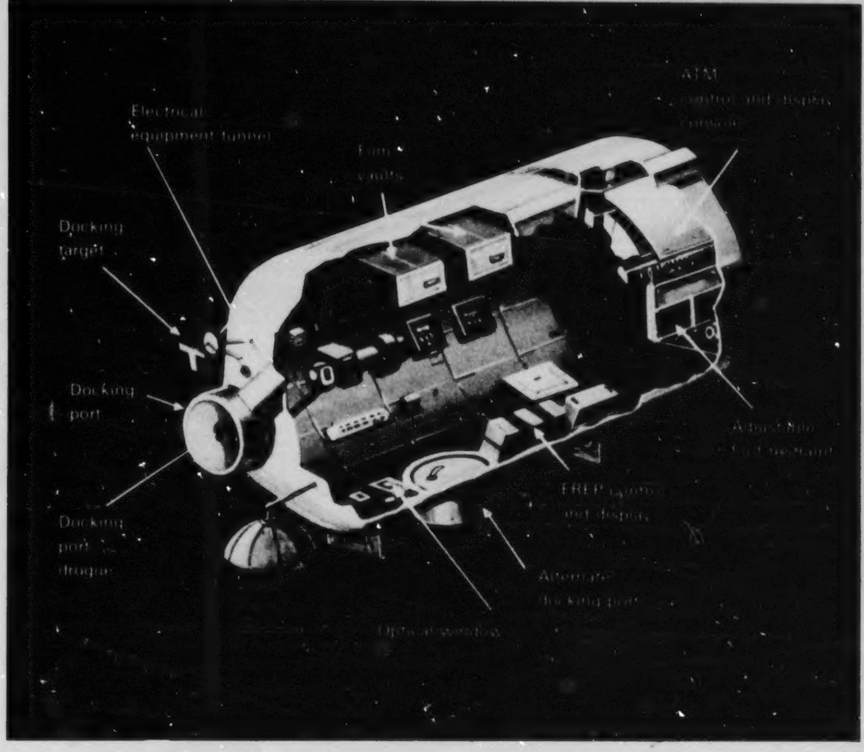
tests had to be scheduled late enough in development so that the test articles would be faithful replicas of flight equipment, yet early enough for their results to be incorporated into the qualification test program. From February through May of 1971 the workshop was put through the 4500-cubic-meter test chambers at MSC; tests of the payload assembly



(airlock, adapter, telescope mount, and payload shroud) began in September and ran through July 1972.[11]

No structural failures, and only a few anomalies, resulted from these tests. Test specifications, however, were changed in several areas of the workshop. Actual testing showed that specified vibration levels were too

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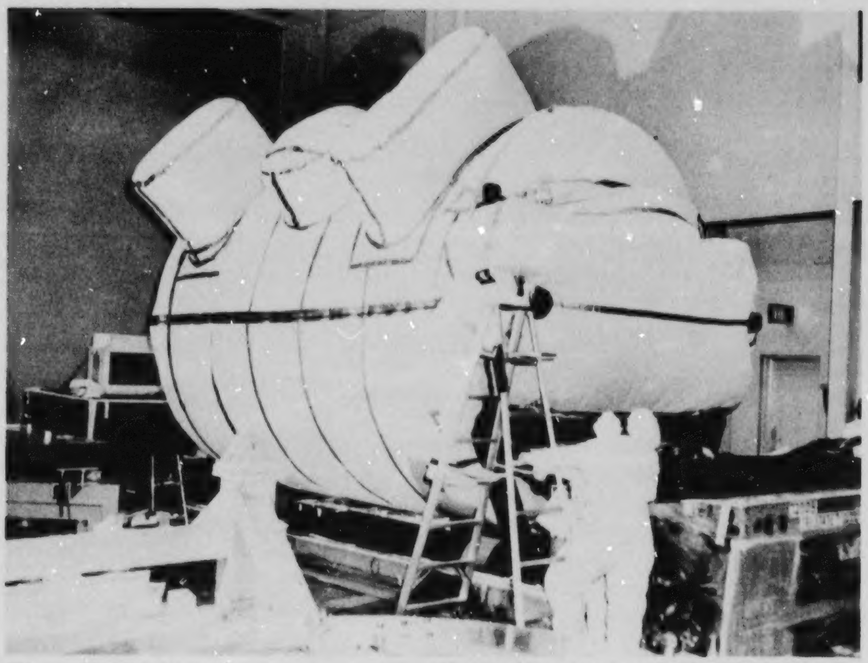
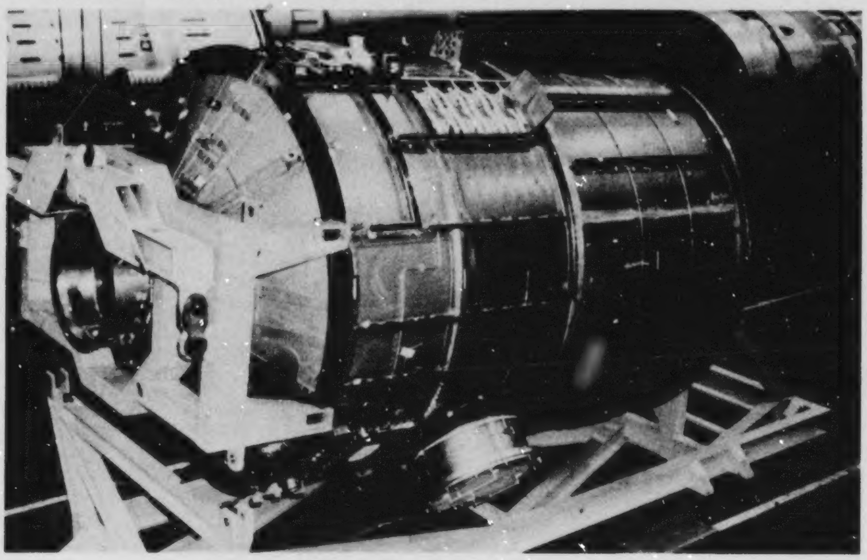


The multiple docking adapter during the Apollo Applications era (1967), top left, MSFC-67-IND 7200-021, *and as built for* Skylab, *bottom left,* ML71-5280. *Above, the flight article being prepared for shipment in December 1971 from Martin Marietta's Denver facility to the McDonnell Douglas plant at St. Louis, where it would be mated to the airlock.* MSFC 026857. *Below, the backup article being prepared for pressure tests.* ML71-7637.



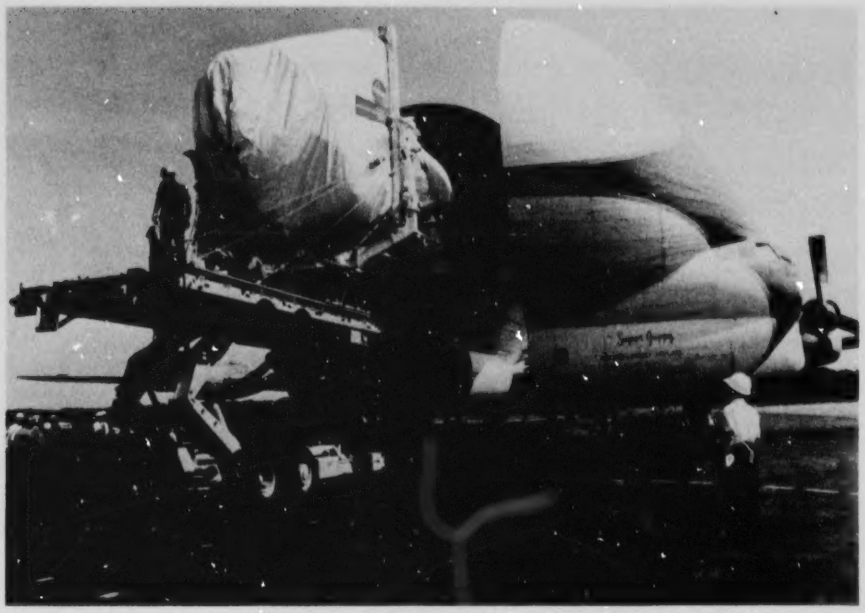
high in 33 of 53 environmental zones of the workshop, and too low in 6. Had those specifications gone unchanged, components tested at too low a level could easily have failed during launch after passing their qualification tests. On the other hand, many components would have unnecessarily failed their qualification tests, necessitating expensive redesign and retesting. The control moment gyros presented a problem of this sort; they could not pass the qualification tests at the vibration levels called for. When a test gyro was run through MSC's vibration tests, however, engineers discovered that the specifications were much too conservative. The specifications were relaxed and the gyros passed without redesign.[12]

TRAINERS AND MOCKUPS

In addition to the test articles, engineering mockups, and flight equipment, both Martin Marietta and McDonnell Douglas built zero-g trainers, neutral buoyancy trainers, and high-fidelity mockups for one-g trainers. The zero-g trainers were usually partial mockups (small enough to fit into the KC-135 aircraft) that allowed weightless testing of critical features of each module, such as crew restraints and extravehicular aids. These trainers and mockups were useful in the developmental phase, while engineers and astronauts were still working out optimum designs, and provided much data applicable to manufacture of the flight articles. Neutral buoyancy trainers consisted of wire-mesh mockups of entire modules; immersed in the big water tank at Huntsville, they served principally to verify the astronauts' ability to move objects within the modules, as well as developing procedures for extravehicular activity. The one-g trainers, accurate replicas of the flight modules containing equipment of the best fidelity available, came into use later in the program as crews began learning flight procedures.[13]

Progress in both the airlock and multiple docking adapter programs was satisfactory during 1971. In December, Leland Belew reported at a midterm program review that neither module had any technical problems that could delay the program. The earth-resource experiments, however, had faltered. Both the infrared spectrometer and the multispectral scanner were snagged on troubles with the coolers that maintained the proper operating temperature for their detectors; the scanner had faults in its data-recording system as well. The multiple docking adapter had already been accepted and delivered to St. Louis for attachment to the airlock, however, and the experiments would be installed there. A cautious estimate predicted that the combined modules could be delivered to Kennedy Space Center by 5 September 1972, as current plans required; but that assumed practically 100% success in the rest of the program.[14]

At St. Louis, engineers worked around the missing earth sensors for another six months while completing other tests and checkouts. By mid-1972 the two modules were ready for the last tests: a crew-compartment



The airlock module and docking adapter arriving at Kennedy Space Center, October 1972. 108-KSC-72P-472.

fit-and-function review, with astronauts methodically verifying every on-orbit procedure; and an altitude chamber test, simulating the performance of the modules in space. No serious discrepancies appeared during these final tests, but some minor testing remained for technicians at the Cape. On 5 October 1972 the airlock and multiple docking adapter, the last of the flight modules to be shipped, were loaded on a *Super Guppy* aircraft* in St. Louis. The next morning they arrived at KSC, where they were unloaded and trundled off to the Vehicle Assembly Building to be stacked atop the workshop.[15]

MODULE DEVELOPMENT: THE WORKSHOP

The workshop project at McDonnell Douglas's Huntington Beach, California, plant bore the brunt of change during 1969 and 1970. Work had started in April 1969, when McDonnell Douglas took S-IVB stage 212 out of storage and began modifying it for its new role. In the course

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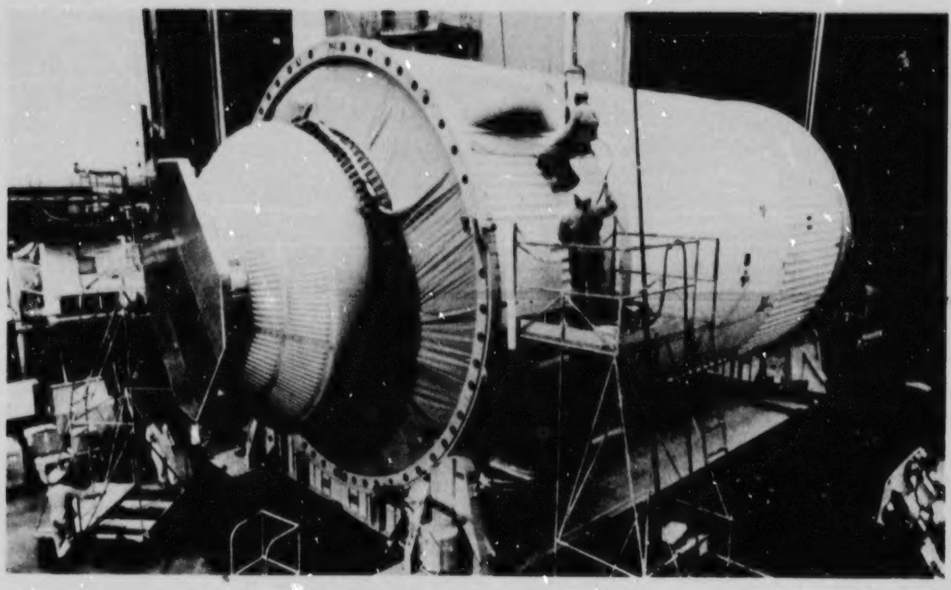
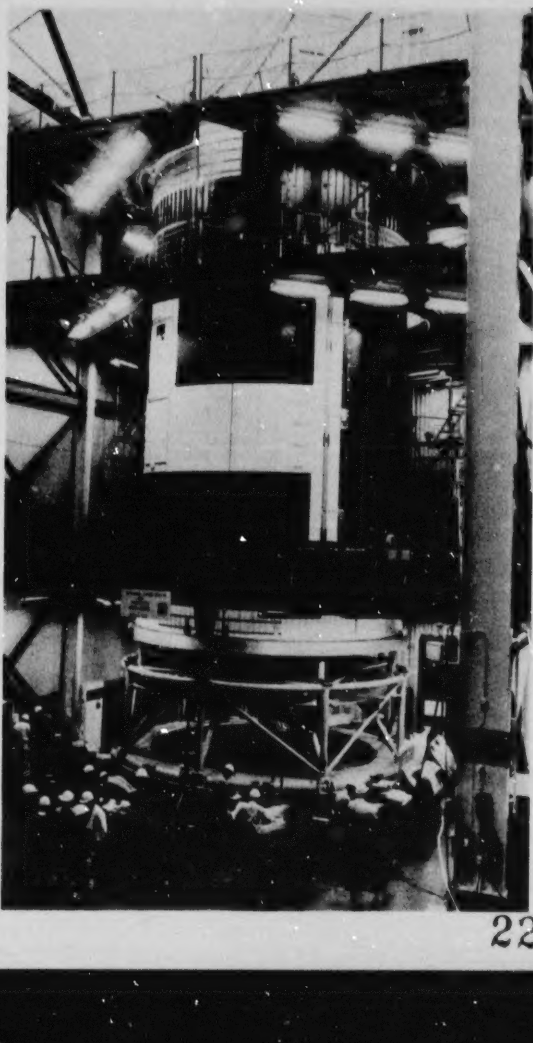
* *Super Guppy* was built for NASA by Aero Spacelines, Inc., in the mid-1960s to carry outsized cargo, principally for the Apollo program. Made from sections of four Boeing 377 Stratocruisers, the plane was for a time the world's largest aircraft in terms of cubic capacity. Its Skylab cargo included the telescope mount and the instrument unit, as well as the CSM.



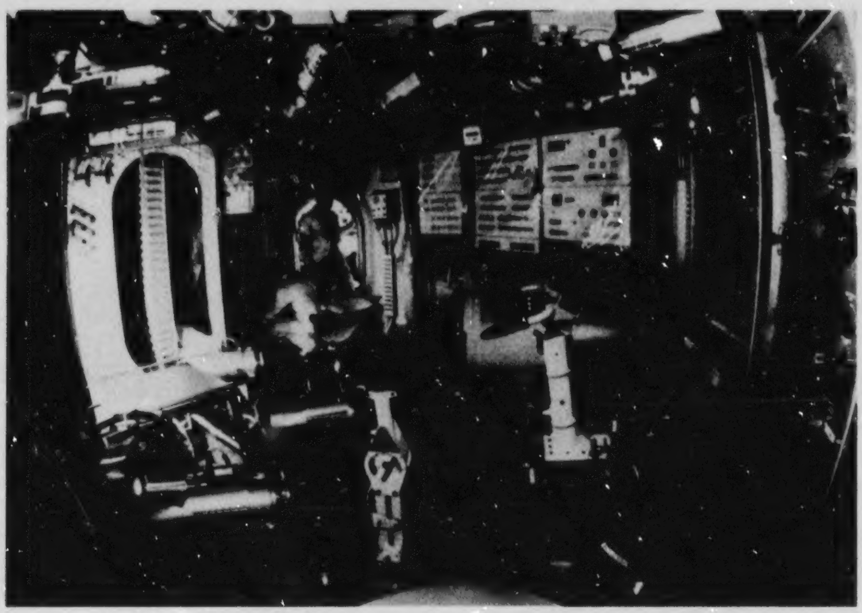


The workshop under construction at the McDonnell Douglas facility in Huntington Beach, Calif. Above, a test version being prepared for shipment to Manned Spacecraft Center, December 1970. 70-H-1628. *Left, the flight unit.* MSFC-71-PM 7234. *Right, wide-angle-lens view of the aft compartment (lower deck) during the crew-compartment fit-and-function test. The ergometer (M171) is in the foreground, the lower-body negative-pressure device (M092) behind the handlebars.* S-72-44799.

of improving the habitability of the dry workshop, Houston's designers completely changed the layout of the crew quarters, added a viewing window to the wardroom, and considerably upgraded the food storage and preparation requirements (chap. 7). Difficulties with the waste management system left its design up in the air until the end of 1970 (chap. 8). New requirements imposed by the earth-resource experiments required a change in the attitude control system (chap. 10). All these changes added to the engineering work load at McDonnell Douglas; the workshop had always been the most complex of the habitable modules, and such top-to-bottom redesign could only delay assembly.

By mid-1971 Headquarters had become somewhat uneasy about the contractor's progress, and the project integration office investigated. The resulting evaluation was about equally critical of McDonnell Douglas and the Marshall project office. It cited inefficient management, some questionable engineering practices, the company's inability to forecast costs and schedules accurately, plus an unwieldy management arrangement among Huntsville's Skylab office, its workshop project office, and the resident manager in California. Recommendations included strengthening Marshall's management, advising the company of its shortcomings, and generally instilling a feeling of urgency into the contractor.[16]

After conferences among Headquarters, Marshall, and McDonnell Douglas officials, Marshall's program manager, Leland Belew, appointed a 24-man Orbital Workshop Task Team headed by William K. Simmons, Jr., manager of the Marshall workshop project. The team's



job, as stated in its charter, was to provide "timely on-site programmatic and technical interface" with the contractor in all matters relating to completion of the workshop; the nickname applied to such groups—tiger team—was more indicative of its role. That role, plainly, was to get the project on track. In August 1971, Simmons and most of his group, which included James C. Shows of the Houston Skylab office and Richard H. Truly of the astronaut corps, moved to California for a year. McDonnell Douglas assigned two key officials at Huntington Beach to its side of the project: Walter Burke, president of McDonnell Douglas Astronautics Company, 26 years with the organization and a veteran of both the Mercury and Gemini spacecraft programs; and Fred J. Sanders, who had been manager of the airlock project before coming to California in 1969.[17]

Simmons and Sanders immediately set up a weekly meeting schedule to review progress and block out future work, and paired off tiger-team members with their company counterparts in several areas of responsibility. Houston's two members were concerned mainly with problems pertaining to crew interfaces. Since those covered nearly every system in the spacecraft, Truly probably had the most hectic job of the lot. He proved to be a hard bargainer when it came to matters of crew convenience and workloads.[18]

At the heart of McDonnell Douglas's difficulty with the workshop was the complexity of *Skylab*'s systems. Thousands of individual parts, some coming from the company's own shops, some from suppliers (including NASA), had to flow into the project in an orderly sequence. Parts that failed, or that had to be redesigned after testing, could cause delays of days or weeks. One of the first discoveries Simmons made was that the contractor had no integrated schedule depicting the sequencing requirements for this flow of components. Another was that information was inordinately slow in percolating down through the management structure to the shops; change orders could take weeks to reach production workers. Simmons moved quickly to establish a master schedule from which priorities could be assigned, and the company moved its deputy operations manager into an office just off the shop floor to expedite changes. While Simmons and Sanders attended to details, Walter Burke's role was to keep abreast of problems and see that necessary jobs were given proper attention. The company president's presence had a salutary effect at all levels.[19]

Simmons's notes to Belew that fall were filled with reports of major and minor snags. Paint flaked off stowage lockers and got scuffed in handling; the workshop window's electrically conducting coating had somehow got scratched; brazed joints in hydraulic tubing were not always reliable. A major worry surfaced when it was found that the iodine used to disinfect drinking water extracted nickel ions from the brazing material. Engineers incorporated an ion-exchange resin in the system, which effectively removed the toxic nickel but pulled out the iodine as well.

Their proposal to get around that problem involved a good deal of work by the crew, and Truly objected. At the same time, tests on the deployment of the workshop solar panels turned up half-a-dozen anomalies.[20]

By mid-October the situation seemed little improved. Looking toward a delivery date of 15 May 1972 for the completed workshop, Marshall Director Eberhard Rees was pessimistic. He urged Burke to do something about his company's poor record, noting that while the airlock and docking adapter had passed 70% and 85% of their qualification tests, the workshop's record was only 25% completion. Two months later, at the Skylab midterm review, Simmons acknowledged that development and qualification testing was still behind schedule. Systems still giving trouble included the thruster attitude-control system, the solar arrays, and the potable water system.[21]

Progress seemed no better in the early months of 1972; as old problems were solved, new ones arose. Starting in March, however, Simmons's weekly reports noted that the checkout program was getting under way; by mid-May, he was looking ahead to the crew compartment fit-and-function review, when crewmen would go through the workshop from top to bottom. That four-day task was completed on 27 May, and the task team started evaluating McDonnell Douglas's proposal to ship the workshop on 15 August.[22]

After 10 months of intensive work, and almost suddenly, the team's work was nearly completed. During June and July preparations went forward for the final all-systems test of the workshop. Started on 17 July, this sequence was completed three weeks later. Only a few anomalies were discovered in the 510 hours of tests, which took every workshop system through its paces. Several items were left to be completed at the Cape, but little remained to be done in California. On 7 September 1972 Headquarters officials, including Administrator James C. Fletcher and Associate Administrator for Manned Spaceflight Dale D. Myers, participated in a ceremony marking acceptance of the completed workshop by NASA. The next day the module, aboard the U.S.N.S. *Point Barrow,* departed Seal Beach for the 13-day trip via the Panama Canal to Florida.[23]

Such a brief discussion of the assembly of the workshop necessarily fails to convey the magnitude of the effort involved. Not only were the workshop systems complex; everything in the spacecraft had to work properly before launch. No partial success, to be corrected on subsequent models, was tolerable. A valid analogy might be a new commercial aircraft—say the Concorde, which was perhaps comparable in complexity to the workshop. If engineers had been required to build the first model fault-free and ready for immediate and unlimited commercial service, supersonic passenger service might still be a hope for the future.

In any event, all the flight hardware was at the Cape by the end of September 1972, ready for stacking and preflight testing.

REENTRY REEXAMINED

While the workshop, with no provision for controlled reentry, awaited assembly and checkout at the Cape, the time came to call for proposals to build Shuttle's launch system. Implementing recommendations made the previous year (p. 354), Deputy Administrator George Low ordered that the request for proposals include the requirement for a study of the reentry hazard created by the large fuel tanks. Similar studies would be required for all future projects.[24]

At the same time Low directed the Office of Manned Space Flight to devise suitable means for deorbiting the S-IVB stages that would take the crews to *Skylab*. On Apollo missions the S-IVB stages had been disposed of in space (solar orbit) or on the lunar surface, but this technique was not applicable to the Skylab missions. When studies showed that the simplest way to deorbit the empty upper stages was by venting excess propellants through the engine, Low ordered this method adopted.[25]

The discussion of the hazards of orbital debris raised questions in the mind of Administrator James C. Fletcher, who had taken over in 1971 after the decision to forego controlled reentry for *Skylab* had already been made. Fletcher, unwilling to accept the risk involved if he had any practical alternative, ordered the matter reopened. With just over four months remaining before launch, program director William Schneider directed Marshall and MSC to study the possibility of using the main engine of the Apollo spacecraft to deorbit *Skylab* as the last crew left it.[26]

Initial reaction from both centers was negative. Besides many engineering problems, Houston found the potential crew hazards unacceptable; if the Apollo should have any trouble undocking after placing the workshop on a reentry trajectory, the astronauts would be in serious trouble. Marshall noted that modifications to the launch vehicle would be required, as well as changes in launch procedures; both would delay launch and increase costs. Just to conduct the necessary studies would take six months, leaving little time to incorporate changes before the last crew was launched.[27]

Nevertheless, Schneider persisted; and in April 1973 a group at Houston began reviewing the techniques and operational procedures for deorbiting the cluster with the service propulsion system of the Apollo spacecraft. By the time the workshop was launched the group was well into its task and had defined many of the problems that would have to be worked. But their efforts were wasted. The loss of the micrometeoroid shield and the damage to the workshop's solar arrays during launch (chap. 14) created too many engineering uncertainties that could not be dealt with. On 13 July 1973 Schneider stopped all studies on controlled deorbit.[28] Whatever problems might be created by the reentry of the workshop would have to be solved later.

12

Preparations for Flight

As Skylab progressed from blueprint to hardware, the program office at Houston focused attention on flight operations. Skylab operations would differ significantly from Apollo missions, in which a series of time-critical events had bound the operation to a rigid schedule. Spacecraft failures were anticipated by contingency plans that left little to chance. In Skylab, extensive earth and solar observations dictated a more flexible schedule. The operations teams in Houston and Huntsville also needed greater staying power; while Apollo missions had lasted no more than two weeks, Skylab's would run for months. Data management was another concern. Unlike Apollo missions, the workshop would be out of contact with ground stations much of the time. Data would have to be stored on board until *Skylab* passed over a ground station, when the telemetry would be "dumped" into a ground receiver. Skylab operations would also force the Houston center into new relationships with Huntsville and the scientific community. Marshall and the principal investigators would exert considerable influence on Skylab. Crew training would have to be expanded to meet the scientific objectives. The dual requirement for training in both science and spacecraft operations laid a considerable burden on Houston's training office and also touched off a lengthy dispute over crew selection.[1]

DEFINING CENTER RESPONSIBILITIES

During Skylab missions, Houston and Huntsville would achieve a remarkable degree of teamwork, quite unlike the disharmony that characterized early Apollo Applications planning. That disagreement had originated in George Mueller's determination to get AAP under way using the lunar module and a low-cost wet workshop. While Houston had no confidence in this concept, Huntsville was willing—even anxious—to develop the hardware. Relations were further exacerbated by Huntsville's desire to have more say in flight operations. As development center for the workshop, MSFC would certainly play an active role; working out the details of this new relationship, however, required lengthy negotiations.

The two centers began preparing for AAP operations in late 1966, focusing initially on communications and the role of Huntsville's Operations Support Center. From time to time, Huntsville officials suspected that their counterparts in Houston were using obstructionist tactics to prevent MSFC's participation in planning and executing AAP flights. Martin Marietta's integration contract, which made no reference to Huntsville's support role, was particularly galling. Nevertheless, it appeared likely at Huntsville that Houston would eventually give ground. Huntsville's involvement with the workshop "made it technically very difficult to exclude [Marshall] from operations support."[2]

In 1967 Huntsville pressed for more responsibility in flight operations. At the very least, the center wanted a supporting role on AAP flights; ideally, the workshop would help Marshall become a leader in spacecraft design and operations. MSC gave ground grudgingly. In June, Director of Flight Operations Christopher Kraft agreed to use Marshall engineers for AAP flight operations, provided they were integrated into his organization. This was unacceptable to Huntsville, which wanted the group to remain separate with the lead engineer reporting to MSC for requirements. By November 1967 the two centers had agreed that Huntsville would staff a Systems and Experiments Section within MSC's Flight Control Division.[3]

By early 1969 it seemed that the two centers were near a modus vivendi. In February, MSC's program manager Robert Thompson assured Belew, his opposite at Marshall, that Huntsville would be kept aware of all developments "by the necessary coordination of our two offices and by MSFC review and concurrence with the evolved operating procedures." Houston would initiate change proposals through Marshall's program office to preclude any appearance of meddling with that center's contractors. Supplemental contracts, added to Marshall's basic contracts, would formalize Houston's relations with McDonnell Douglas and other firms.[4]

Huntsville officials were pleased with these concessions, but still wanted a formal agreement spelling out the "total operations interface." Such an agreement, while recognizing Houston's direction of mission operations, would also honor Marshall's "cradle-to-grave" responsibility for hardware. Huntsville exercised this responsibility for its launch vehicles, analyzing their performance in flight and establishing operational procedures and limits. KSC's launch team, offspring of the von Braun organization, considered Marshall's involvement on Saturn tests a natural extension of its design responsibility; Huntsville hoped to gain similar recognition from MSC for Skylab operations. At an April planning meeting, Marshall's staff approved a recommendation that the center seek "an active voice in real-time operations decisions affecting either individual MSFC hardware modules or the integrated cluster."[5]

Two months after the dry-workshop decision, center representatives met in Houston to discuss operations. MSC reviewed its specific requirements for flight planning, Huntsville outlined the functions of its support center, and a debate on management philosophy ensued. Before adjourning, the two sides reached agreement on several points: (1) The mission requirements document, prepared jointly by the two program offices, would serve as the basic instrument for mission planning, and both offices would use it as their formal communications link to MSC's operations team; (2) Houston would prepare the operational data book, using information from Huntsville and contractors; and (3) Marshall would provide Houston access to its configuration control boards.[6]

Other aspects of Skylab operations, however, continued to divide the two centers. While Houston sought to upgrade the workshop, Huntsville clung to the no-change dictum. Matters reached a low point at the telescope-mount design review in May 1970 when, as an MSC official recalls, the two sides "slugged it out to a standstill." Thereafter, relations improved markedly, and by year's end the two centers had agreed on the basic framework for Skylab operations. A flight management team, comprising program managers and MSC's operations managers, would set policy. Although Houston had a majority on the team, Huntsville and KSC were assured a voice in all matters. Daily operations remained in the hands of MSC's flight control teams. If problems involved hardware, the flight director could seek assistance from a Marshall liaison team stationed nearby in the Flight Operations Management Room. The liaison team could, in turn, call for help from a much larger group of engineers at Huntsville's operations center. An elaborate communications system tied the two centers together, providing Huntsville with detailed information on *Skylab*'s condition.[7]

OPERATIONS PLANNING IN HOUSTON

Attitudes in Houston changed appreciably after *Apollo 11* and the dry-workshop decision (pp. 109–10). Until July 1969, most MSC officials viewed Skylab as an unwelcome diversion; after the lunar landing, it became the next major program.

The Flight Control Division began preparing an operations plan in August 1969. Division Director Eugene Kranz hoped to retain many Apollo features in the Skylab operation, but certain changes were dictated by the longer missions and the larger number of flight systems. Houston could not afford to keep a full complement in its Mission Control Center throughout the Skylab missions, as it was doing for Apollo. Besides, an earth-orbital mission required less support. During the astronauts' working hours, a "high-level" shift would run operations; at night MSC would maintain a skeleton crew with additional engineers on call. A second concern involved staffing of the mission control room, the heart of Houston's operations complex. Two flight controllers divided the responsibility for spacecraft systems on Apollo. Since *Skylab* had five distinct units (including the telescope mount), a similar division, plus other requirements, would bring the staff to nearly 30 engineers. Kranz feared that such a large group might hamper the flight director: "You would end up caucusing instead of making decisions." His preliminary plan allowed one systems expert for each spacecraft; the plan also consolidated some other duties. With these changes, Kranz expected to have no more than 20 flight controllers in the control room during periods of peak activity. Normal operations would require only 11.[8]

Kranz renewed Skylab planning in November as part of a larger review conducted by the flight operations directorate. Manning requirements were a major topic, but a number of other issues were also discussed: the impact of the new 50° orbital inclination on operations, Houston's relations with principal investigators, and the requirements for unmanned operations. Kranz listed 11 aspects of the Skylab operation that had no precedent in Apollo missions and asked for a thorough review of these "key mission issues."[9]

During the next 30 months, the flight-control organization was restructured. Several instructors were retrained as systems engineers. Men assigned to the experiments required extensive training; several took lengthy courses in solar physics. In October 1972, one flight-control team was assigned full time to Skylab. One of its first tasks was to develop procedures for data processing; another was to conduct several mission simulations with the flight crews. After *Apollo 17*'s splashdown, the rest of the division turned its full attention to Skylab.[10]

When the missions began, the division's preparations proved sound in most areas. One exception proved to be the transmission of data. Signals transmitted from the spacecraft were picked up by 1 of 13 stations in the tracking and data network and forwarded through Goddard Space Flight Center to Houston. About a quarter of the time, *Skylab* would be close enough to a station to transmit data as it was acquired. Most of the time, however, data were recorded to be "dumped" when the workshop reached the next station. *Skylab*'s telemetry system required only five minutes to transmit data that had taken two hours to gather.[11]

The system was a major change from Apollo, and Houston's flight-control teams had trouble adjusting. On lunar missions, flight controllers had seen only 10% of the data, but they had been able to call up specific information when needed. Increased telemetry from the workshop and the long periods between transmissions ruled out immediate access to data during Skylab. Instead, using a process called "redundancy removal," only changes to data reached Mission Control. The new equipment was installed late, and some flight controllers failed to master it. The shortcoming became rather painful during the crisis that followed launch of the workshop. According to Kranz: "Because of the lack of proficiency in the data retrieval task, the flight controllers were generally inefficient in accomplishing contingency analyses." After the first manned mission, 12 persons were trained specifically for data retrieval.[12]

While Kranz's division prepared for operations, the Flight Crew Operations Directorate began work on a Skylab flight plan. Eventually, a plan would provide a detailed schedule for each crew's activities in space. The initial drafts, however, served different purposes. They were, first of all, training vehicles for flight planners who found their Apollo background of limited value. The drafts also served to point up crucial issues, define crew-training requirements, and uncover problems with experiment priorities. Much of the necessary information came from the mission requirements document: objectives, experiment requirements, extravehicular activity, recovery zones, information on television and photography. General guidelines for scheduling crew activities were set within the Flight Crew Operations Directorate. Initially, these guidelines were fairly rigid (e.g., all crewmen would eat together), but as scheduling complexities increased some flexibility was allowed. Although computers were used, the actual scheduling was done by hand. The goal was to meet all the objectives of the mission requirements document. When this proved impossible, the program offices revised the document, usually reducing the number of times certain experiments were repeated. The books, checklists, cue cards, maps, and charts used in planning each mission totaled more than 10 000 pages.[13]

HUNTSVILLE ORGANIZES FOR MISSION SUPPORT

Huntsville began preparing for mission support in mid-1970 by identifying 17 major tasks and appointing a manager to handle each requirement. The Mission Operations Office coordinated planning principally through monthly meetings of task managers, prime contractors, and representatives of Marshall's major divisions. Much of 1971 was spent preparing documents; in the end 19 plans for mission support were written. Marshall engineers met frequently with the Houston operations team; a particularly important series of meetings in mid-1972 reviewed hardware characteristics and operating procedures. In October Huntsville tested two years of work with a mission simulation, a prelude to participation in Houston's dress rehearsals.[14]

Marshall consolidated its support in the Huntsville Operations Support Center, an organization that had proved itself during Apollo. Skylab requirements would be handled by 10 mission support groups, each staffed to service a major system, e.g., attitude control. Initial manpower projections for the support groups totaled more than 400 engineers, some to be drawn from the program office, others from MSFC laboratories and contractor teams. Saturn engineers would monitor launch vehicle operations during checkout and early stages of flight. Other personnel managed a complex communications network of voice, television, and high-speed digital-data lines connecting Huntsville with Houston and the Cape. The Mission Operations Planning System, an asset unavailable during earlier manned missions, allowed support personnel to draw on Houston's computers for immediate printouts of current flight and experiment data.[15]

MSFC officials divided the Skylab mission into five phases. Prelaunch support began in October 1972. During this phase both launch vehicle and workshop engineers would be at KSC's call. The second phase, workshop launch and deployment, lasted only a few crucial hours but produced peak activity at the support center. Launch of a crew represented a third phase; the first part of each launch would also require peak operations. Manned operations were the fourth phase. The support center's coordinating staff would serve at full strength while the astronauts were at work and at partial strength the rest of the time. Members of the mission support groups would handle Skylab problems during the normal work week. Nights and weekends, they would remain on call for emergencies. The last phase, unmanned operations, required MSFC monitoring, because several workshop systems continued to operate, as did the solar telescopes.[16]

TEST PILOT VS. SCIENTIST-ASTRONAUT

The choice of Skylab crewmen was bound to cause hard feelings among Houston's astronauts. The group had expanded rapidly in the mid-1960s, and as NASA's fortunes declined it was clear that some of them were not going to fly—at least not until the 1980s. The problem was aggravated by Houston's selection policy. As director of flight crew operations, Deke Slayton determined who would fly. His recommendations went through Gilruth to Headquarters, but Slayton's choices were usually approved. He placed a premium on experience; consequently astronauts moved in a natural progression from Gemini flights through service on Apollo backup crews to an Apollo flight. His policy favored those pilots who had entered the program by 1963 and those test pilots in the 1966 group who received an early assignment. At a disadvantage were the scientist-astronauts brought into the program in 1965 and 1967. By the time these men had finished the required year of Air Force flight training, they were last in line.

Dissatisfaction among the scientist-astronauts surfaced after the first lunar landing. Despite speculation that subsequent missions would

Astronaut Joseph P. Kerwin removing experiment equipment from a storage locker on the top deck of the workshop trainer. During the missions, unpacking and restowing equipment and supplies would take a surprising amount of time. S-72-40260.

stress science, Slayton chose only test pilots for the next three Apollo flights. In October 1969, scientist-pilots complained to Headquarters about selection criteria that emphasized operations at the expense of science. Slayton's rebuttal stressed the hazards of a lunar mission—no one would benefit from a dead geologist on the moon—and downplayed the importance of scientific competence in lunar exploration.[17]

During 1970 opportunities for the scientist-astronauts declined further. In January NASA canceled one Apollo flight; in September, two more. It seemed likely that no scientist would explore the moon. Late that year the Space Science Board sought assurances from NASA that two scientists would fly on each Skylab mission. The board's action coincided with a resurgence of dissatisfaction among the scientist-astronauts in Houston. Homer Newell, NASA's top-ranking scientist, went to Houston in January 1971 to hear their complaints and see what could be done about them. One by one the scientist-astronauts told Newell that they could not get a fair shake as long as a test pilot (Slayton) picked the crews. As they saw it, his choices were determined by flying time, special skills, and personal relations. Science was not a consideration; in fact, those who showed more interest in science could be at a disadvantage. Several astronauts recommended that Headquarters establish criteria for crew membership, preferably with some appreciation for science. The group felt strongly that each Skylab mission should include two scientists. One of them noted, "flight operations take only a small fraction of the time required for science and other objectives."[18]

Newell incorporated much of what was said in his recommendations to the administrator. On the sensitive issue of crew selection, he urged that Harrison Schmitt (the only astronaut with a Ph.D. in geology) be assigned to a lunar landing as early as possible and that two scientists be considered for each Skylab flight. He also proposed a review of NASA's crew-selection process and suggested restructuring the scientist-astronaut program to allow a greater commitment to a scientific career. Since he had heard only one side of the issue, Newell labeled his recommendations "tentative."[19]

The recommendations touched off several months of debate concerning the makeup of Skylab crews. Slayton and Gilruth argued against more than one scientist per flight, reasoning that hardware problems would demand a high level of systems expertise, an area in which test pilots were thought to excel. Gilruth informed Dale Myers in June that reliability studies indicated "a high probability of systems problems . . . during the mission." Since the workshop's systems could not be modified after launch, Houston was directing most of its training to "systems management and malfunction procedures." He also pointed out that Skylab missions had been planned around a concept of maximum cross-training, which would give each crewman roughly the same degree of proficiency on all major experiments. Consequently, an astronaut's specific academic background was relatively unimportant.[20]

Myers wanted to accommodate the scientists by including a second scientist on at least one mission, but Gilruth's arguments were persuasive, and Myers remained undecided. When three Soviet cosmonauts died on 29 June during reentry, however, he agreed that NASA should give operational considerations top priority. On 6 July Myers recommended approval of Houston's plan for Skylab crews; two pilot-astronauts would go on each mission with one scientist-astronaut. On the first flight, the scientist would be a physician. Myers left selection of specific crew members to Houston. Newell expressed some misgivings, but the plan was adopted.[21]

Crew selections were made late in the year and formally announced on 19 January 1972. Charles "Pete" Conrad, the ranking Skylab astronaut, headed the first crew. Conrad had flown three previous missions, commanding *Apollo 12*'s flight to the moon. Two astronauts new to spaceflight made up the rest of an all-Navy crew. Joe Kerwin had earned his M.D. at Northwestern University before joining NASA in 1965; Paul Weitz had entered the program a year later. Alan Bean, commander of the second mission, was the only other veteran selected for Skylab; he had gone to the moon with Conrad in November 1969. Owen Garriott, an electrical engineer with a Stanford Ph.D., filled the scientist's slot and Jack Lousma, a Marine major, received the pilot's assignment. Another Marine test pilot, Gerald Carr, headed the third crew, which included Edward Gibson, a Caltech Ph.D., and Air Force Lt. Col. William Pogue.* The selections represented a compromise among NASA interests: less experience—only two veterans—than Slayton wanted and fewer professional scientists than Newell wanted.[22]

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* App. E contains biographies of the Skylab astronauts.

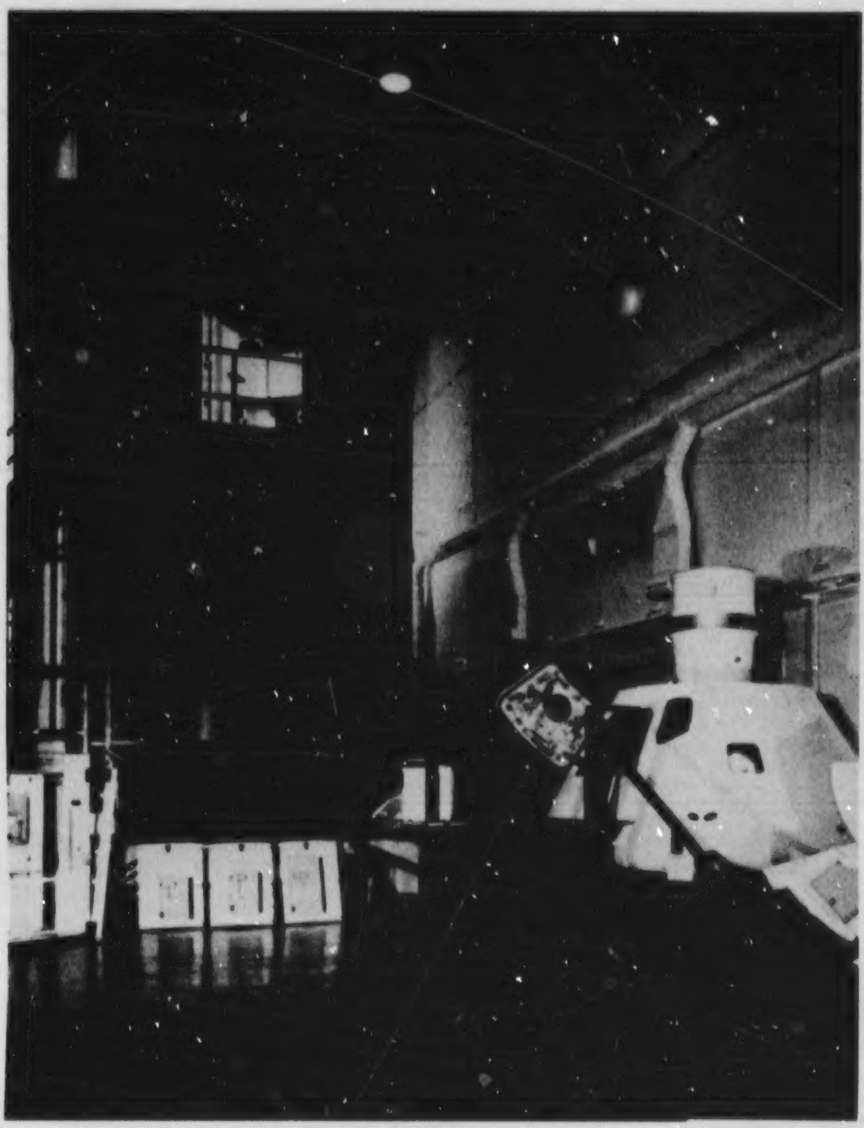
In retrospect, the importance of crew makeup was overstated. On all three missions, test pilots performed experiment work creditably while scientist-astronauts proved adept at repairing spacecraft systems. Success depended more on teamwork and individual attitudes than on academic training. Although the medical directorate had fought hard to send a physician on the second mission, their fears about a 56-day flight proved groundless. Apollo telescope mount experimenters were well served by Garriott and Gibson. Ideally the second or third crew should have included an earth-resources specialist, but the earth-resources experiments had been added late in the program and none of NASA's scientist-astronauts was particularly qualified with the hardware. Furthermore, given the experimental nature of those instruments, expertise might have been wasted. Slayton's contention that the flight plan would allow little time for independent research proved largely correct.[23]

Crew Training

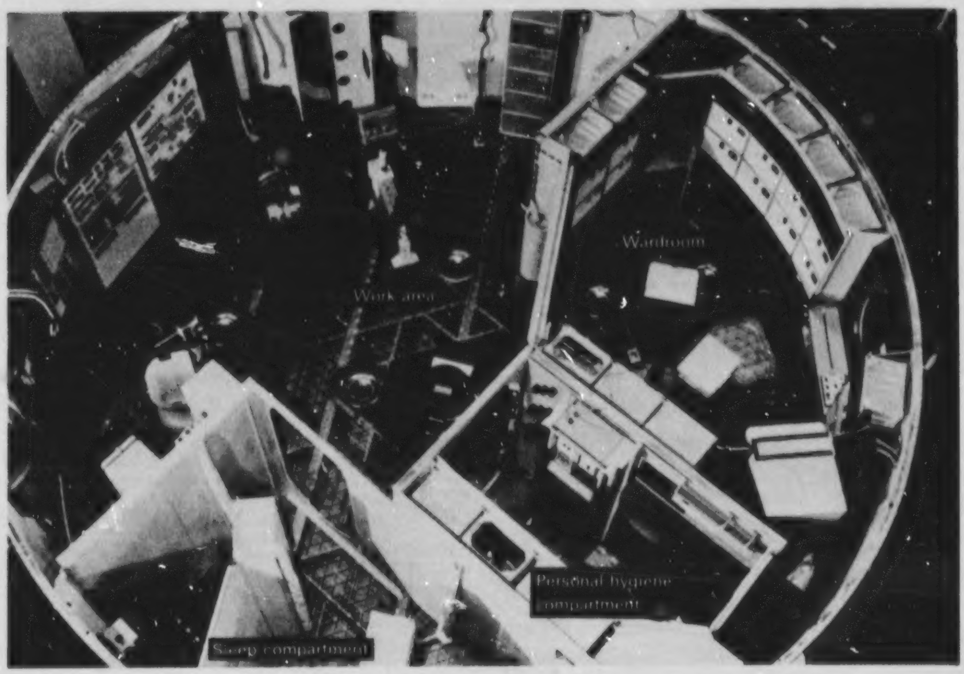
Crew training began in October 1970, largely because of prodding from the Apollo telescope mount investigators. The Naval Research Laboratory's Richard Tousey had first approached Houston about a solar physics course for astronauts in 1967. He renewed his request in February 1970 in a strong letter to the program office. Recounting his earlier suggestions, Tousey noted "that little has been done as yet to arrange for scientific training of the crew." He acknowledged that astronauts could operate the telescope mount without an understanding of solar physics, but the data thus obtained would be inferior. For that reason NASA had promised that its crewmen would have appropriate scientific training. Tousey feared that Houston's procrastination would necessitate a cram course a few months before launch, "when systems operational training will be paramount." Ideally, training should begin 24 months before liftoff. With a July 1972 launch date (according to early 1970 schedules), there was little time to waste.[24]

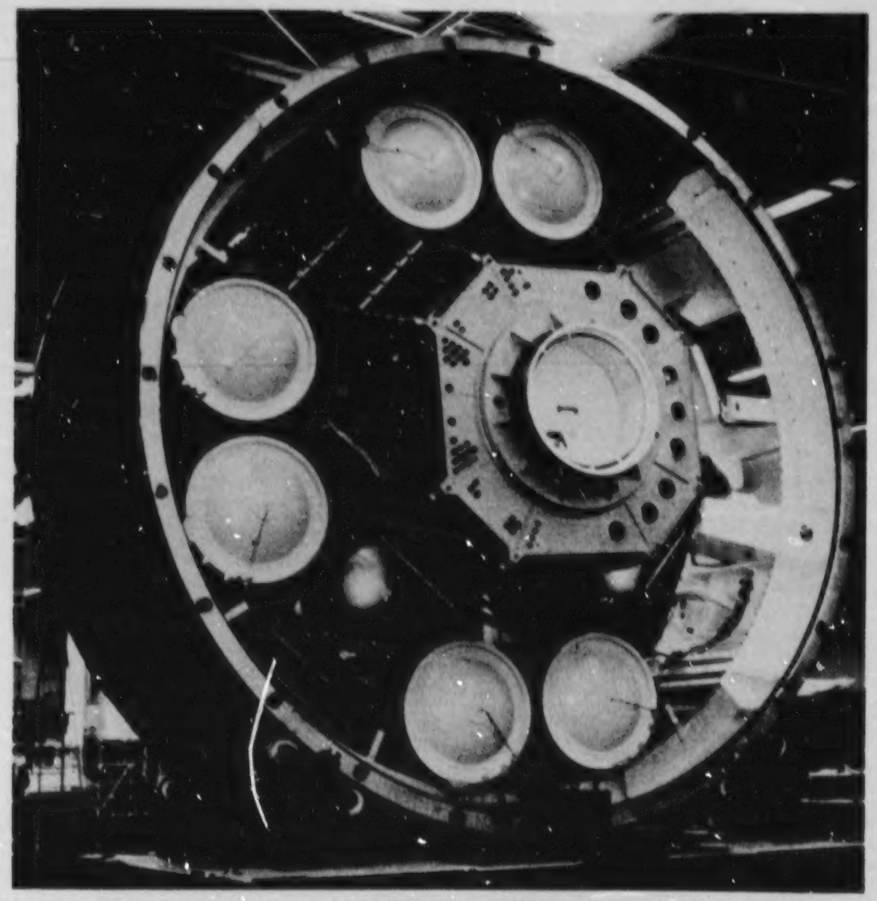
Houston was not particularly eager to begin crew training, for the astronauts were heavily involved in design reviews and training chief John Von Bockel had his hands full with Apollo. By June, however, MSC had taken steps to satisfy the telescope-mount investigators. At a meeting in Denver, it was agreed that Skylab astronauts would begin a 10-week, 60-hour course in solar physics that fall. Principal investigators would take an active part. All crewmen would be given the same level of training, regardless of their background.[25]

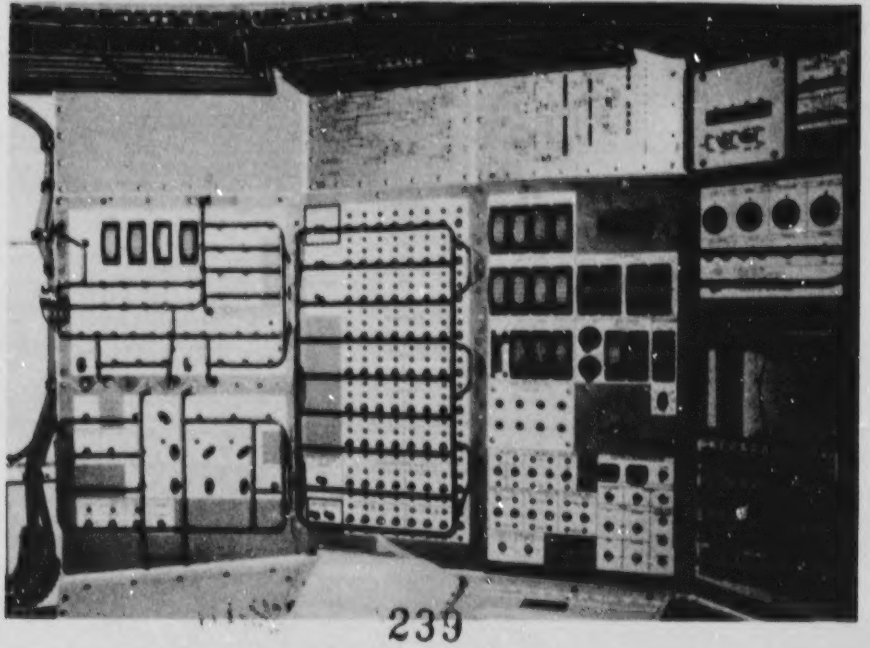
Principal investigators were generally pleased with the course outline prepared by Dr. Frank Orrall, University of Hawaii physicist. Tou-



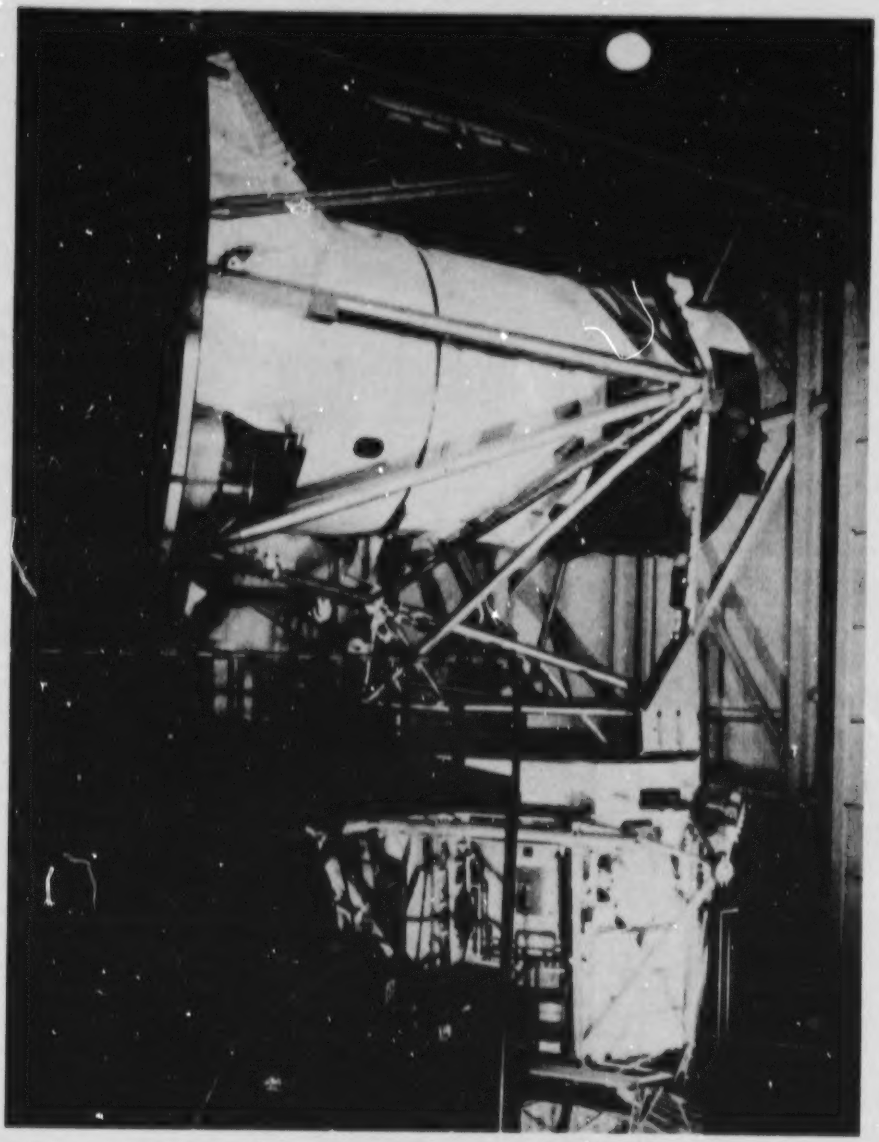
The one-g trainer at Manned Spacecraft Center. Above, exterior of the workshop and Apollo command module. ML71-7650. *Right above, upper deck (forward compartment) of the workshop. The square port with the coiled metallic hose hanging on it, left of center, is the scientific airlock. The double ring of storage lockers and water tanks would be easily accessible in zero g.* S-72-51657. *Right below, the lower deck with compartments labeled.* ML72-5059. See following pages for remaining modules of the trainer.


Wardroom
Work area
Personal hygiene compartment
Sleep compartment





The one-g trainer, cont. *Top left, the airlock module mounted to permit lateral rotation. The space between the fixed shroud and the airlock carried atmospheric gases under high pressure (6 cylindrical tanks of oxygen, 6 spherical tanks of nitrogen).* ML71-7655. *Below, the airlock, docking adapter, and telescope mount. The black ring at left is the fixed shroud. The telescope mount, at the head of the stairs, is deployed in flight attitude. Unlike the other modules, the telescope mount had no interior work space; astronauts would work only on its exterior.* ML71-7653. *Bottom left, power supply and circuit breaker panels inside the airlock.* ML71-7649.



sey suggested several changes, including observations of the sun during the course, rather than afterward. He also proposed to augment Orrall's presentation with several lectures on the role of solar physics within the larger framework of science. He hoped this would stimulate the astronauts' interest by pointing up the applications of solar physics "outside the study of our sun as merely a thing in itself."[26] When the course got under way in late October, most of the astronauts found the instruction quite a challenge. One admitted, "I was right up to my eyeballs in trouble the whole time, trying to keep up and understand what was going on." Most of them had trouble communicating with the investigators—professionals in an esoteric specialty. For Jerry Carr, the course went much better after he gave up trying to be a solar physicist and instead looked for ways to become a competent observer.[27]

While the astronauts were learning solar physics, MSC's training office began work on a much larger program encompassing all Skylab training. Robert Kohler took the lead in preparing the syllabus, assisted by a team from Martin Marietta. Kohler laid out a 2200-hour program stretching over 18 months. The schedule was based on a 28-hour training week; previous programs indicated that astronauts would spend another 20 to 25 hours in travel, physical exercise, flying, and reviews. Kohler's program included 450 hours of briefings and reviews, 450 hours of experiment work, and nearly 700 hours of simulator training. It was a demanding schedule compared to Apollo missions, which had averaged 1200 hours of training.[28]

Briefings constituted a large part of training in 1971. Experiment

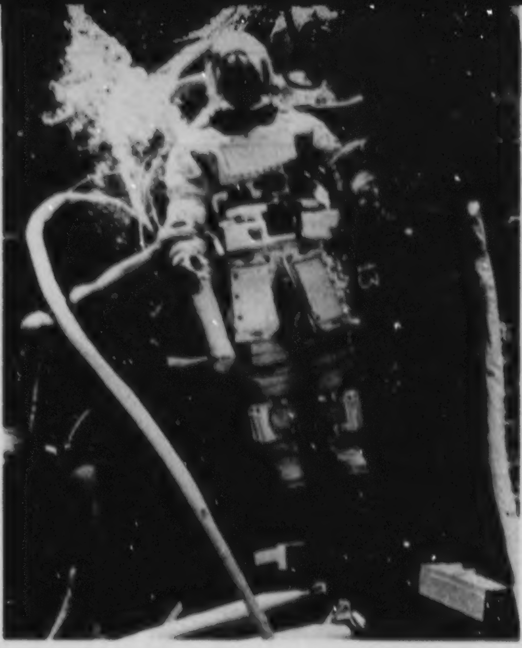
Astronaut Charles Conrad, Jr., training at the display and control panel of the telescope mount. S-73-20339.

The first crew training with the medical experiments. Kerwin is in the rotating chair used for the human vestibular function experiment M131, while Weitz records. Conrad is riding the bicycle ergometer in the background. 72-H-1262.

briefings were handled in two phases. Principal investigators lectured the astronauts on the theory, objectives, and judgment involved in gathering data; later, Martin Marietta instructors provided a nuts-and-bolts presentation on operational procedures, maintenance, safety, and support equipment. North American Rockwell conducted a lengthy block of instruction on the Apollo spacecraft—130 hours of briefings and nearly twice as much time in the simulator. Although Skylab crews would spend relatively little time in the Apollo spacecraft, those few hours would encompass a number of events where an error could prove fatal. The largest block of instructional time was devoted to the workshop, with Martin Marietta covering the telescope mount and McDonnell Douglas the remaining systems.[29]

Through most of 1971, the training office worked its schedule around spacecraft testing. Traditionally, astronauts had played an active role in testing flight hardware. The Skylab syllabus provided 100 hours for this purpose; the crews would eventually spend twice that much time. The scheduled hours, moreover, reflected only part of the time actually invested. Most tests were conducted at contractor plants or other NASA centers. Frequently, crews would travel to Huntsville or St. Louis only to have a test postponed. Schedule slips at Huntington Beach were the biggest headache; workshop delays cost the training office hundreds of man-days. After the missions were completed, Von Bockel would recommend against astronaut participation in future spacecraft testing.[30]

A number of other training requirements kept astronauts on the go. Crews reviewed navigational stars and received instruction on the stellar experiments at the Morehead Planetarium in Chapel Hill, North Caro-



Practicing extravehicular activity in Marshall's big water tank. After being used extensively during the design phase of Skylab, the Neutral Buoyancy Simulator proved to be the best place to train for working outside the spacecraft. Such work was carefully planned and then timed in the tank. 72-H-1093.

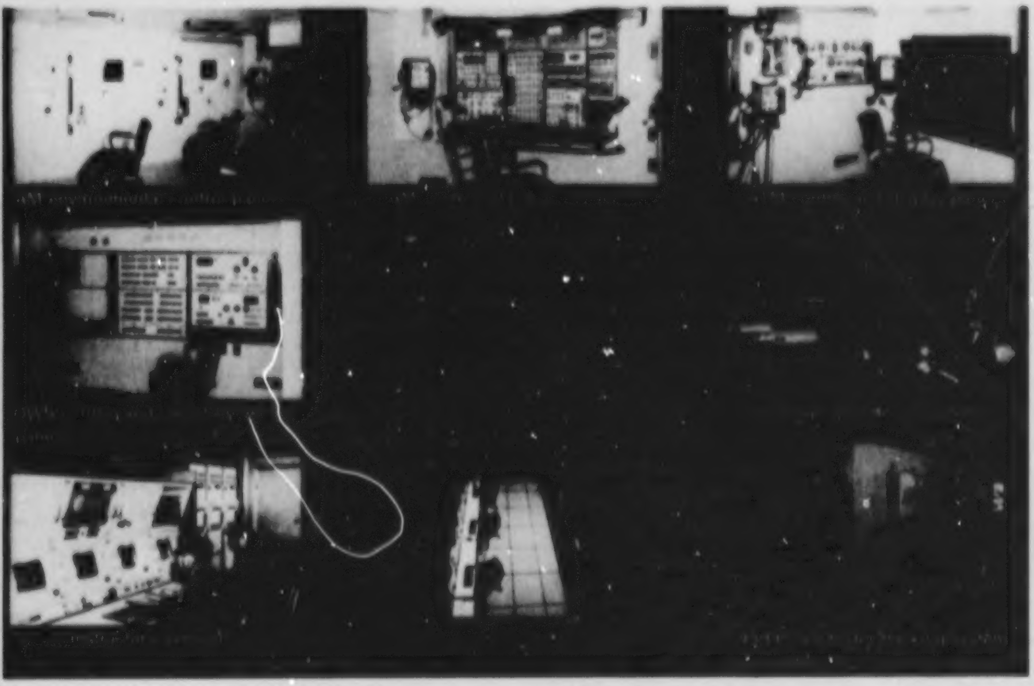
lina. Work with the astronaut maneuvering units took them to Denver and to Langley Research Center in Virginia. Apart from spacecraft testing, extravehicular training in Huntsville's neutral buoyancy trainer (p. 170) required the most travel. Beginning in February 1972, one crew or another used the tank nearly every month.[31]

Training moved from theory to practice in early 1972 when crewmen occupied the Skylab simulators. A computer system in the workshop mockup displayed images similar to those the astronauts would see in flight. The telescope mount console was its most prominent feature; crewmen spent as much as 200 hours studying solar activity on its video screens. The computer could also display normal and abnormal conditions on a half-dozen other control panels. Frequently, while one crew trained in the workshop, a second worked in the command-module simulator, practicing flights to and from *Skylab*. Two other Apollo simulators provided special training for launch aborts and rendezvous procedures. Astronauts could operate the simulators independently or in conjunction with Mission Control. When complex display systems were not required, crews worked in one-g mockups, training models that duplicated the *Skylab* configuration.[32]

Houston's basic principle was that all crewmen should become proficient with the major experiments; at the same time, however, the variety of systems required a degree of specialization. The commander was given responsibility for the Apollo spacecraft; the scientist took charge of extravehicular activities, the solar telescope, and medical experiments; workshop systems and the earth-resources equipment fell to the pilot. This division of labor was apparent in the training performed by the crews. Conrad, despite his considerable flight experience in the command module, spent 400 hours in the Apollo simulators, 55 hours more than Paul Weitz. Weitz, in turn, spent nearly twice as much time on earth resources as either of his crewmates. Kerwin's preparation for the medical experiments, 181 hours, considerably exceeded that of either of his partners. The pattern generally held true for the other crews. The syllabus was a guide rather than a rigid yardstick. Schedules could be changed by the crew commander and the mission's training coordinator. Commanders exerted a great deal of authority; for example, Conrad insisted that 20 hours was not enough training for workshop activation, and his crew eventually spent 125 hours mastering the task. Instructors evaluated progress by operational competence demonstrated, rather than hours of exposure.[33]

The start of "mini-sims" in September 1972 marked the transition from individual to team training. These sessions in the workshop simulator kicked off at 6:00 a.m., reveille on a mission day, and ran until bedtime at 10:00 p.m. The crew received instructions from a teleprinter as it would in flight. Voice contact with the ground was limited to times when the simulated flight brought the workshop over a ground station,

The extensive Skylab simulators. S-72-116-S.



Astronaut Charles Conrad, Jr., training with the human vestibular function experiment M131, March 1973. The sphere and a magnetic rod were used to indicate body orientation nonvisually. The chair rotated and tilted forward, backward, and side to side. S-73-20695.

but instructors could answer specific questions at any time. Mini-sims were an excellent investment of time; crews benefited from the integrated training, and flight planners uncovered a number of scheduling constraints.[34]

Pressures mounted in the last months before launch as training schedules were disrupted by simulator breakdowns, reviews, and last-minute demands on the astronauts. By January 1973 the first crew had fallen behind schedule and work weeks stretched to 60 hours. Late that month Bill Schneider moved the workshop launch from 30 April to 14 May because of delays at the Cape. The extra two weeks gave the training office a little breathing room, but the crews continued to work at a hectic pace.[35]

After the missions were over, Von Bockel was reasonably satisfied with the training program, though he would have made some changes. He had sought unsuccessfully to train only one backup crew, considering the 5000 man-hours invested in the second as unnecessary. Slayton, however, needed two; since one prime crew included a doctor and the other two a physical scientist, he had to be prepared to replace both. Von Bockel acknowledged that his instructors did not always stay ahead of the students. The astronauts were eager to learn, and program engineers seldom ignored their questions. "If the crew wanted to know something," he recalled, "people seemed to come out of the woodwork." Instructors, on the other hand, frequently had trouble getting information. Von Bockel recommended that in future programs, training materials should be prepared well in advance of instruction.

Skylab's biggest training problem, as indicated by the flights, was the long interval between instruction and performance of certain critical tasks. The last crew's deactivation and reentry came 13 weeks after training, and they made a procedural error—quickly rectified—that could be attributed to unfamiliarity with procedures. Von Bockel recommended that future missions allow time for refresher training during the flight.[36]

13

Launching Skylab

August 1972 brought back memories of Apollo's heyday at the Kennedy Space Center (KSC). In one high bay of the Vehicle Assembly Building, *Apollo 17*—the last vehicle of the lunar landing program—was completing its final tests before rollout to the pad; the booster for *Skylab* occupied a second bay; and in a third was a new 39-meter pedestal that would serve as the launch table for manned Skylab missions. The scene pointed up Skylab's close ties with Apollo: the programs shared common facilities, operations, and hardware. Since 1970, one office had directed both programs. Despite the similarities, Skylab introduced important changes. Saturn IB launches shifted from Cape Canaveral to NASA's complex 39. The payload of the workshop required different equipment and tests; in particular, the experiment hardware added a new dimension to the checkout.

Launch preparations, including the facility modifications, required considerable debate; but once decisions were reached, the changes went smoothly and at relatively little cost. Launch operations encountered more difficulty. Checkout revealed many defects typical of new flight hardware, but officials had expected problems and the schedule allowed for delays.

SELECTING THE LAUNCH COMPLEX

High among George Mueller's goals for Apollo Applications had been the continued employment of the Saturn industrial team. Reductions in NASA funding had dashed his hopes, and by mid-1968 KSC officials faced the problem of maintaining a Saturn IB launch team during a long period of inactivity. The team numbered nearly 3000, some 90% of whom were contractor personnel; and more than half of these were employed by stage contractors. For Saturn IB rockets, Chrysler Corporation's Space Division built, tested, and launched the first stage; McDonnell Douglas the second stage; and IBM the instrument unit.

Other contractors were responsible for design engineering and maintenance of communications, propellant systems, and structures at launch complexes 34 and 37. During seven years of Cape operations, the Saturn IB team had compiled an impressive record of 14 launches without a failure. The Apollo schedule in early 1968, however, called for the transfer of manned missions from Saturn IB to Saturn V after the *Apollo 7* flight in October. Saturn Vs were launched from complex 39 on Merritt Island. When the first Apollo Applications mission was postponed to late 1970, KSC faced at least a two-year hiatus in Saturn IB operations.[1]

After studying the problem and considering the conflicting interests involved, Mueller approved a plan that cut manpower at the Saturn IB launch complexes by 87%, leaving a skeleton crew of 350. The two complexes would be kept in a standby condition, with the removable equipment in storage and the principal structures periodically sandblasted and repainted. Even so, the number of people retained for their specific operational skills was larger than needed for maintenance, the mix of maintenance skills was not the most economical for the job, and retention of key personnel would prove difficult. The alternative—organizing a new Saturn team in 1970—was even less attractive.[2]

As KSC officials pondered ways to maintain a IB cadre, a parallel study examined the possibility of using another launch site. There were disadvantages to both Saturn complexes on the Cape. LC-34 was old, undersized, and showing the effects of salt-air corrosion. Originally an Army project, its design had suffered from inadequate funding. During seven years of use, the complex had undergone major modifications including changes to support manned flights. LC-37 had been designed by NASA engineers in 1961 with a better understanding of Saturn requirements; its service structure, launch umbilical tower, and blockhouse were more appropriately sized to IB operations. But it had not yet been altered for manned launches, and that change would take nearly two years.[3]

The Advanced Programs Office at KSC wanted to launch AAP missions from the newer LC-39 on Merritt Island; consolidation of manpower and equipment there would save money and improve operations. Complex 39 differed from the IB complexes in two major respects. First, because of the Saturn V's huge dimensions, everything on complex 39 was oversized. Second, it embodied the mobile launch concept. At the older complexes on the Cape, technicians assembled the rocket, stage by stage, on the pad. On Merritt Island this was done within the controlled environment of the Vehicle Assembly Building. Then a crawler transported the rocket and mobile launcher to a pad five kilometers away for final checkout and launch. A 136-meter tower on the mobile launcher performed the functions of the older stationary umbilical tower. Eight service arms on the launcher tower provided electrical, pneumatic, and propellant services to various stages and modules of the space vehicle;

astronauts used a ninth arm to enter the command module. A mobile service structure, which stood opposite the tower at the pad, provided access to other points on the vehicle. LC-39 had two pads, but only one mobile service structure, which was essential for manned missions.[4]

The biggest problem in launching the IB from LC-39 was adjusting the launch facilities to the smaller rocket. Since an Apollo stacked atop a Saturn IB was 43 meters shorter than the Apollo–Saturn V, much of the supporting equipment would not be correctly positioned. Service arms 7 through 9 connected with the Apollo spacecraft on a Saturn V; those arms would swing far above a spacecraft stacked on the Saturn IB. Relocating the service arms was no easy task; they were actually mechanical bridges, 18 meters long and weighing up to 25 tons. Five of the arms supported the vehicle until launch and could swing clear in 2–5 seconds (hence the popular name *swing arm*). Work platforms in the assembly building and on the mobile service structure posed similar problems. While the work platforms did not have to swing, they were also large. Those in the assembly building were 18 meters square and up to three stories high. Besides relocating the arms and platforms, the launch team would have to reposition propellant, pneumatic, and electrical lines that nearly covered the back side of the mobile launcher.[5]

In a February 1969 study on launching the IB from LC-39, Boeing proposed to minimize modifications by placing the Saturn IB on a 39-meter pedestal so that the second stage and instrument unit, as well as the Apollo spacecraft, would stand at the same height as the Saturn V configuration. Thus the launch team could use the launcher's upper service arms and the work platforms of the service structure and assembly building. The modifications were estimated to cost about $5 million, one-third the cost of a new launcher. The biggest design problem involved the dynamic characteristics of rocket and pedestal at liftoff. Hold-down arms on the launcher restrained the vehicle for four seconds after the engines ignited while launch control ascertained that all systems were working properly; during this time, the thrust stretched the rocket's frame upward. If the engines suddenly shut down, the vehicle would rebound with considerable force. The pedestal would have to be strong enough to absorb that force without dangerous oscillations. Boeing suggested further studies of the rocket-pedestal dynamics.[6]

In 1970, following NASA's decision to complete the lunar landings before Skylab, debate reopened on launching IBs from LC-39. Grady Williams, chief of design engineering, had little quarrel with the Boeing report. Since the pedestal was the chief question mark, his office had undertaken a geometric evaluation and tentative layout, sized the pedestal members, and performed a preliminary stress and weight analysis. His deputy had found some misgivings in Huntsville about vehicle-pedestal dynamics and wind loads at liftoff, but Saturn officials seemed willing to make the change. Williams concluded that the modifications would not delay Skylab.[7]

Walter Kapryan, director of launch operations, pointed out several disadvantages to the change. With only one pedestal for the IB launches, KSC faced a tight checkout schedule, requiring weekend work and reducing operational flexibility. If the pedestal were seriously damaged in a launch mishap, repairs could delay the last crew beyond the eight-month life of the workshop. But operations on LC-39 would save money, particularly if NASA reached a quick decision and shut down LC-34 and LC-37. Ray Clark, director of technical support, believed the tentative estimate of a $10 million saving was too conservative and that the difference might be half again as much. He noted that dual operations on LC-39 would pose a problem during hurricane season. The center had only two crawlers to move three large structures—the two launchers and the mobile service structure. Since each transfer took seven hours, the launch team would have its hands full if a hurricane approached.[8]

From Huntsville, Saturn manager Roy Godfrey also asked for an early decision: first, to save money on LC-34, where modifications to ground support equipment were costing nearly $4000 a day; and second, to leave sufficient time for changes on LC-39. Allowing for a six-month study of the pedestal design and a year of wind-tunnel tests and data analysis, Huntsville needed to begin its design work in mid-July. Godfrey did not insist on an unmanned launch to test the pedestal, but he expected close center coordination in reaching a decision. He argued that the benefits of the change should cover "not only the identified cost impacts and program risks but also the probability [of additional costs and risks] when detailed analysis and tests are accomplished."[9]

The view was much the same from Houston, where the potential savings from an LC-39 operation offset reservations about a manned launch from an untried pedestal. The change to LC-39 would help MSC's principal contractor, North American Rockwell, by avoiding a transfer of Apollo equipment from Merritt Island to the Cape and reducing the manpower required for launch operations. Much of the savings would be lost, however, if decision was delayed beyond 15 May. Houston was well along in design work for LC-34 equipment and expected to let material contracts by June.[10]

In presenting its case to Debus on 23 April, the Skylab Office emphasized that LC-39 operations would save considerable sums, while demonstrating the versatility of the Merritt Island complex. Questions during the presentation ranged widely. Did the cost estimates for LC-34 include rehabilitation costs? The answer was no. Debus inquired about the purpose of the wind-tunnel test and the possibility of disputes when nonunion workers from Chrysler joined union personnel on LC-39. At the conclusion, the director polled his staff and found general support for the proposal.[11]

A meeting in Huntsville that same day disclosed more doubts. The Marshall staff considered launching a vehicle from the pedestal as a "major technical risk" that simulations and dynamic analysis could not resolve; doubts would remain until the first launch. Huntsville's support for the move to LC-39 was contingent upon several requirements: a pedestal load test to confirm its rigidity, a pull test to measure vehicle stiffness, and three months of additional checkout time to resolve unforeseen problems.[12]

All parties wanted the matter settled soon; a decision after 15 May would diminish savings and a delay beyond 1 June would result in "unacceptable cost and schedule risk." At a meeting of officials from the four program offices on 27 April, Program Director Bill Schneider said that a goal of 15 May was probably unrealistic since the matter required the approval of the administrator. Anyway, Schneider was more concerned about testing the pedestal. He asked, "How do we prove we can safely launch from LC-39?" Prevailing opinion at KSC was that tests and data analysis would provide sufficient confidence in the pedestal. The deputy Saturn manager at Huntsville considered the cost savings a persuasive reason for using LC-39, particularly with NASA "under every type of pressure to limit operating costs." After the need for a trial launch was debated, Schneider closed the meeting by stressing that operational advantages should weigh more heavily than cost considerations.[13]

Decisions in Washington came sooner than Schneider had expected. On 29 April 1970, Myers tentatively authorized a changeover, at the same time barring any irreversible action. Administrator Paine gave verbal approval on 11 May, and four days later the congressional space committees were notified of NASA's intent to use LC-39. In June Schneider asked KSC for "substantiating data to show that flight-crew safety standards will not be degraded." Morgan subsequently sent Headquarters a plan that included design reviews, dynamic and stress analyses, a wind-tunnel program, and several pull tests to measure the deflection of the vehicle and pedestal.[14]

Outside KSC, doubts about the pedestal lingered. In November 1970 the program offices again considered the merits of a trial launch to train the crew and prove the system, when Chrysler officials suggested a static firing as a training exercise. After a review by the program managers, Schneider concluded that KSC's plan was sound. His recommendation against a trial launch was accepted by the Management Council the following month.[15]

THE MILKSTOOL

The pedestal (*milkstool* in local parlance) was Skylab's most distinctive feature at LC-39. Weighing 250 tons, this was a stool for the likes of Paul Bunyan. Four legs of steel pipe more than a half-meter in diameter supported the launch table. The columns stood 15 meters apart at the base but leaned inward to less than half that width at the top. Horizontal and diagonal pipes braced the structure. Viewed from above, the launcher table with its 8.5-meter exhaust hole resembled a huge doughnut. On its deck were hold-down and support arms, fuel pipes, and electrical lines. A removable platform over the exhaust hole allowed technicians to service the eight engines of the Saturn IB's first stage.[16]

Design work began in July 1970. Buchanan rejected Chrysler's bid to build the pedestal under a sole-source contract, considering the design "very difficult to fabricate . . . and apt to become distorted from the initial bath [Saturn exhaust]." Chrysler's argument that its proposal would expedite matters carried no weight, since KSC had included time for competitive negotiations. In subsequent bidding, Reynolds, Smith, and Hills (architects for the mobile launcher) won the pedestal contract. KSC opted to design the pedestal's support systems in its own shops.[17]

The biggest problem in designing the pedestal was to minimize vertical and horizontal vibrations. The requirements eventually set forth by Huntsville allowed only the slightest sag under very heavy loads, yet the designers were limited in the weight they could use to achieve the desired stiffness. Since the Saturn V was a near-capacity load for the crawler, the pedestal could weigh little more than the stage it replaced. KSC engineers set that figure at 225 metric tons. The effects of the Saturn's exhaust had to be considered. Although flame temperatures would approach 2700 K, it was uncertain how much of this would impinge on the pedestal. Wind loads were still another factor. During operations at the pad, the service structure would deflect much of the wind and an arm connected to the top of the rocket would damp vibrations. Neither protection, however, would be available in the final hours of the countdown. Wind-tunnel tests established a maximum permissible wind speed of 32 knots for launch. Designers considered connecting the pedestal to the launcher tower for added strength until studies showed that the pedestal would actually be stiffer than the tower.[18]

Construction of the pedestal produced the only major contractual dispute over Skylab's launch facilities. In the fall of 1970, the Small Business Administration asked that the contract be set aside for one of its firms. KSC refused, stating that an "experienced total organization" was required to prevent slips in the six-month schedule. Since the pedestal was Skylab's pacing item, any delays would have a serious effect on the entire program. In asking for open bidding, the center also cited "precision tolerances of alignment and elevation far exceeding the normal industry standards." Unable to change KSC's plans, the Small Business Administration sought help in Washington from its congressional committee and NASA Headquarters. The matter dragged on for more than a month, keeping plans at a standstill. Finally in late December, Headquarters ruled in KSC's favor. But when bids were opened a month later, Holloway Corporation, a small electrical firm in nearby Titusville, submitted the low bid, $917 000. Worse yet from KSC's viewpoint, the proposal called for fabrication by another small firm in Jacksonville. Fortunately, the episode had a happy ending. In spite of problems securing the steel pipe, Holloway and its associates completed the work on time and to specifications. Afterward, the Small Business Administration wrote Congress a letter chastising NASA for its reluctance to use a small firm.[19]

PREPARING A LAUNCH PLAN

In its early planning, KSC shared the frustrations of other Apollo Applications offices as schedules were continually revised. The dry-workshop decision provided a firmer basis on which to work, and by December 1969 the center had a preliminary launch plan. A major assumption was minimum time on the pad. Whereas Apollo operations normally took 8 weeks there, the Skylab Office aimed for 24 workdays, minimizing exposure to the weather and reducing the cost of launch operations (which in the final month ran to about $100 000 a day). The center would do as much work as possible inside the assembly building, including removal of work platforms from the workshop's interior. Access to the workshop on the pad would be limited to contingencies, e.g., testing the water supply, checking a questionable instrument reading, or installing a late experiment.[20]

Veterans in the Launch Operations Office doubted that the center could maintain such a tight schedule, and for the next year pad time and access were hotly debated. Charles Mars, Skylab project leader for the operations group, believed the principal investigators would demand, and ultimately gain, late access to their experiments. He wanted to plan accordingly, leaving access platforms in the workshop during rollout and allowing pad time for the scientists. At a September 1970 review of the launch schedule, Debus sided with the program office, emphasizing that "pad access would be by exception only." To Mars's surprise, the center held firm to this position for the next 30 months.[21]

While the workshop remained off limits, other pad requirements extended the schedule beyond the original projection. By June 1970 planned pad time had increased to six weeks, counting two weeks for contingencies. When Huntsville objected, KSC eliminated the cushion, but estimates continued to rise. At the December program review, Paul Donnelly, associate director for operations, presented a 44-day schedule, including 30 workdays. The biggest increase—9 days—involved filling and testing the oxygen and nitrogen tanks that provided the workshop's atmosphere. Donnelly agreed to review the matter further and determine what requirements could be compressed. In early 1971 the operations office did reduce the time allowed and scheduled other tests in parallel. Thereafter, planned pad time remained at 30 days.[22]

The operations plan laid out for the workshop in 1971 employed a building-block approach. Components and systems of each major module would be checked out individually. Then, midway in the eight-month schedule, technicians would stack the space vehicle and begin integrated systems tests. These were particularly important because the major modules had not previously been mated, either mechanically or electrically. Before rollout the launch team would stow food, film, and other consumables. Because experience showed that the first launch in a manned program brought many unanticipated problems, the Skylab schedule ran several months longer than a typical Apollo operation. The extra months also allowed for an increase in launch activity: after August 1972, not one but three vehicles would be in work at LC-39. *Apollo 17*'s launch in December would reduce the load, but four months later KSC faced its first dual countdown, leading to Skylab launches 24 hours apart. The magnitude of the operation warranted an early start.[23]

Launch of a Skylab crew required less planning, since it was essentially an Apollo operation. The extensive operations in earth orbit required new stowage plans and some new test procedures. More importantly, the change of launch sites dictated an early trial run of the LC-39 facilities. Highlights of the schedule included the only mating of the Apollo spacecraft with the docking adapter prior to liftoff, and the test of the pedestal in January 1973.[24]

FACILITY MODIFICATIONS

Facility modifications were part and parcel of the operations debate, much of the discussion focusing on a new "contingency" arm for access to the workshop. The December 1969 plan called for entry through the side door, a new feature that KSC had lobbied for. In the assembly building, technicians would reach that door from service platforms; at the pad a new swing arm would provide contingency access. In 1970, the arm became the principal means of access to the workshop. The launcher's uppermost service arm (9, which Apollo astronauts used to board the command module) was relocated adjacent to the workshop's side hatch. An airlock, designed to protect the interior of the workshop from contamination, replaced the Apollo white room at the end of the arm. Rather than build a second airlock for operations in the assembly building, the engineering office recommended that the new arm be used there also.[25]

By the end of the year, plans for access to the rest of the space vehicle were settled. Much of the traffic to the airlock and multiple docking adapter was routed over the new swing arm. Once inside, technicians moved up the stack through the workshop's forward dome hatch. While the vehicle was in the assembly building, the telescope mount could be reached from access ramps on the top work platform, which had been fitted with another clean room. KSC had not planned to service the telescope mount at the pad, but in mid-1970 Huntsville identified several service requirements, and arm 8 was chosen for this purpose.[26]

Much of the debate on Skylab operations centered on the mobile service structure, the only major item at LC-39 without a backup. The structure could be moved, but the five-kilometer trip between pads took about six hours. If operations at pad A required the service structure, pad B went unsupported for at least a day. Kennedy planners initially ruled out using the service structure for the workshop, but during the discussions on a IB launch from 39, Hans Gruene, director of launch vehicle operations, challenged that decision. Loading cryogenics into S-II stages had sometimes cracked the insulation, requiring inspection and repair on the pad, and Gruene saw no reason to believe the problem would not recur during Skylab. If the service structure were not available, an alternate means of access to the S-II would have to be devised or the rocket would have to be returned to the assembly building. The staff acknowledged the problem but did not consider it serious enough to rule out the transfer of the IB operation.[27]

Events that summer confirmed Gruene's prediction. In July, Huntsville stipulated that the S-II insulation would be inspected on the pad. There seemed little choice but to use the service structure for such work. While workmen could reach any part of the Saturn V from a bosun's rig, their activities were severely limited. Using the service structure for both Skylab vehicles, however, posed obvious scheduling difficulties and a few design problems as well. The payload shroud on the workshop was nearly three meters larger in diameter than the Apollo spacecraft. If workmen were to service the S-II stage from the service structure, the bottom platform would have to be extended.[28]

The matter bounced back and forth between KSC offices for several months before it was settled. In October, Kapryan agreed to modify the lowest platform, although the change would leave only one platform to service the lower half of the IB rocket. He recommended that the bottom platform be restored to its original configuration after launch of the first crew, so that all work stations would be available for the last two missions, pointing out that the loss of one day in the operation would cost more than the $85 000 modification. His proposal was approved.[29]

A few other modifications were necessary to adapt Saturn V facilities to the smaller IB. The five swing arms that serviced the lower stages of the Saturn V were replaced by a single arm, modified by adding a three-meter extension to reach the IB booster. Umbilical lines and a withdrawal mechanism were brought from LC-34. In the assembly building, a new workstand was built to reach the structural section between the two stages. In the launch control center, 19 firing panels were installed for IB operations. KSC's propellants team faced a problem on the pad; the liquid oxygen system pumped 37 850 liters per minute into the Saturn V, four times the rate the IB could accept. Rather than alter the system, the Saturn V's replenishment system was used. It pumped 4540 liters per minute, about half the desired rate.[30]

Initial payload testing—except for the workshop—took place in the Operations and Checkout Building, eight kilometers south of complex 39. The most notable change was the addition of a clean room for the telescope mount. Located in the building's high bay, the room rested on a support system that was designed to permit calibration of the experiment optics; specifications called for the plane of the floor to move less than five seconds of arc in a 24-hour period. Adjacent rooms housed the air conditioning unit and ground support equipment used to test the telescopes. A second modification altered the dimensions of the integrated test stand used for systems testing on the Apollo spacecraft, placing the command module at the bottom level and allowing an important mating test between the spacecraft and docking adapter. In a less noticeable change, the Apollo laboratories were modified to accommodate Skylab experiments.[31]

The first pieces of the pedestal arrived at the construction site outside the assembly building in April 1971. The pipes were sandblasted, painted, and welded into six-meter sections. Baseplates were installed on the launcher floor, and by early May the pedestal was taking shape. The eight segments of the launch table came in mid-June. The table was placed atop the pedestal in early July and an access bridge from the launcher was added shortly thereafter.[32]

That fall contractors outfitted the pedestal and began constructing the clean rooms. The pedestal work included the installation of engine service platforms, new fuel and power lines, and a quench system to cool the exhaust. The clean room in the checkout building got off to a late start because of problems with a partition between *Apollo 16* operations and the Skylab work. By Christmas, however, the work was on track. The modifications in the checkout building continued without a major problem.[33]

HANDLING THE EXPERIMENTS

For checkout purposes, experiments were divided into three groups according to complexity. About half fell into the simplest category, which did not require continuous support from the development center or contractor. This hardware was normally installed before it reached Kennedy and was not removed for test purposes. Experiments in the second group warranted continuous support from the developer. Most of this hardware required off-module testing. The group included about 40% of the experiments, including the earth-resource instruments and most of the corollaries. The third group, preflight and postflight medical experiments, involved no functional hardware, and the development centers retained responsibility for preparations.[34]

The testing of experiment hardware was complicated by the many interfaces. *Skylab* carried over 70 experiments, most of which connected to or operated in conjunction with other experiments and flight hardware. As one example, the ultraviolet panorama telescope, developed in France to photograph stars, had eight separate parts that interacted with each other and with seven other items of flight hardware. Altogether, the telescope depended on 41 interfaces for successful operation; of these, more than half had to be tested at the launch site. The French instrument was in group one, the less complicated experiments. The many interfaces were tracked with a fit-check matrix, a chart that listed all hardware connections and when they were verified.[35]

Most of the checkout was performed by module contractors; thus an experiment mounted in the workshop was tested by McDonnell Douglas. Contractors were responsible for receiving inspection, bonded storage and handling, installation and removal of experiment hardware, preparation of documents, planning and coordination of the checkout, and resolution of anomalies. When hardware was removed from the module, responsibility reverted to the development center, working under Kennedy management.[36]

Principal investigators were considered to be representatives of the development center. Although they were not directly involved in the prelaunch checkout, many participated in the operation. A Kennedy engineer assigned to each experiment served as the point of contact, and the scientists were encouraged to review test procedures and data. The responsible centers arranged the investigators' activities in advance, however, to minimize interference with the test schedule. The investigators were handled with care; some of them had political connections in both the legislative and executive branches and would not be shy about complaining. As a rule, investigators who did not visit the Cape were less tolerant of test restrictions. Those who saw the complexity of the operation at first hand accepted its constraints.[37]

RELATIONS WITH HUNTSVILLE

The launch team had little trouble defining spacecraft test procedures with Houston, since the command and service modules differed little from their Apollo counterparts. Coordination with Huntsville was another matter. For much of the planning phase, Marshall and Kennedy were at loggerheads over workshop test procedures. The problem was twofold. Huntsville was used to dealing with Hans Gruene's launch vehicle operations team, a group that had once been a part of Marshall. Over the years, the Saturn engineers developed a close relationship. Checkout of the workshop, however, came under Ted Sasseen's spacecraft operations office, with which Huntsville had worked little. Establishing new relationships usually takes time and this proved no exception.

but adjustment was made more difficult by Marshall's overzealous concern for its Skylab hardware—or so it appeared outside Huntsville. NASA's practice was to have design centers define test requirements from which Kennedy prepared test procedures. The centers reviewed the procedures, ironed out areas of disagreement, and the launch team then conducted the test. In this case, Huntsville seemed determined to run the operation, particularly the first integrated-systems test. The two centers took more than a year to reach a compromise.[38]

A second dispute concerned preflight tests of the telescope mount. Its checkout represented the first time that a manned spaceflight center was to perform tests at the launch site (previously contractors had done the actual testing), and some misunderstanding was likely. The full extent of the disagreement came to light in December 1970 at a review of telescope mount flight procedures. Gene Cagle, engineering manager for the telescope mount, took immediate exception to the Kennedy position that his group would perform as a contractor. Even had Huntsville been willing to assume the subordinate role—and it was not—Cagle lacked the manpower to meet Kennedy's requirements. The preflight procedures listed 73 forms that the test team would maintain, many of which required several signatures at various levels. Cagle contended that he had barely enough people to do the actual checkout, much less fill out the paper work. He also objected to the requirement for quality assurance. He estimated that it would take 700 men, three times the number he had, to comply with Kennedy's rule that an inspector must verify each testing step. Furthermore he objected to the launch center's applying its philosophy of quality control to a Marshall operation. At Huntsville, the testing organization assured the quality of its own work.[39]

Kennedy officials turned a deaf ear to Cagle's criticisms. Their procedures embodied wisdom acquired over many years in the launch operations business. The atmosphere at the Cape before a major launch was quite different from the relatively relaxed conditions of checkout at Huntsville. With thousands of people pushing towards the same deadline, a formal system of paper work was essential. Short cuts inevitably brought on bigger problems. Besides, contractors managed to work within the system. Cagle's request for manpower assistance from Kennedy was denied, since it violated the center's checks-and-balances philosophy. Neither side appeared willing to give an inch, and the meeting was temporarily adjourned.[40]

It took nearly a year to bridge the gap. Spacecraft operations helped by lending Cagle some systems engineers from its liaison team in Huntsville; that group followed the telescope to Houston and then to the Cape, working as part of Huntsville's test team. Kennedy also agreed to perform quality checks, as Houston was doing for the thermal vacuum tests. Marshall in turn attempted to meet Kennedy's other requirements. The actual checkout of the telescope mount went very smoothly; afterward Debus recognized the test team's work with a letter of commendation.[41]

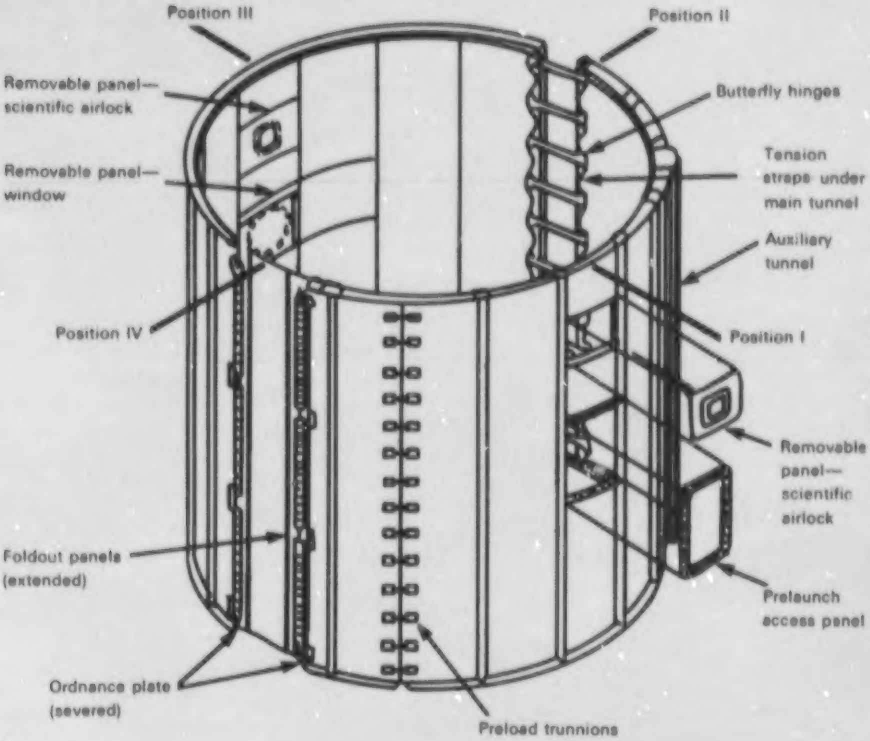
Problems of New Hardware

When flight hardware arrived in mid-1972, the launch team moved to center stage, where it would remain for the next nine months. The first spacecraft (CSM 116) arrived aboard NASA's *Super Guppy* on 19 July and moved directly to the Operations and Checkout Building. The following week the spacecraft underwent inspection in an altitude chamber. During the next two months, the checkout would be scheduled around *Apollo 17* requirements.[42]

The workshop's S-IC booster (number 513, the 13th flight article in IC stage production) arrived from New Orleans aboard the barge *Orion* on 26 July. By 22 August all four propulsion stages for the first two vehicles were on hand. Skylab's pace quickened after the *Apollo 17* rollout and the Labor Day break. During the next two weeks, the stages were mated atop their launchers. On 22 September the workshop and payload shroud completed a two-week trip from Huntington Beach, California, on the *Point Barrow*, a specially equipped vessel of the Navy's Military Sealift Command. The telescope mount flew in aboard *Super Guppy*. Within a few days, the workshop joined the Saturn V in high bay 2.[43]

Early operations went smoothly, in large part because the launch team was working with proven equipment and procedures. One of the first new tasks, deployment of the meteoroid shield, ended the clear sailing. The test, scheduled for 3–7 October, was a milestone, since technicians could not enter the workshop until the deployment was verified and the shield refitted around the access door.[44]

Before conducting the test, McDonnell Douglas had to rig the shield in its launch configuration, snug against the workshop wall. In a job somewhat like fastening a corset around a sleeping elephant, 32 technicians wrestled the 545-kilogram shield into place around the workshop. Trunnion bolts running the length of the shield were then tightened to draw it against the outer skin. The fit was unsatisfactory. Several bulges remained, and there were two-centimeter gaps along the upper and lower edges of the shield assembly. The basic problem was that the flight shield differed in several respects from the static-test article, which had been used for earlier deployment tests. After several futile attempts to follow the prescribed procedure, the launch team began experimenting. Technicians loosened the bolts that fastened the ends of the shield's 16 panels, pushed the panels against the tank, and retightened the bolts. The gap remained. The panels were manipulated in other ways with little more success. McDonnell Douglas finally called a halt and scanned the shield


Position III
Position II
Removable panel—scientific airlock
Butterfly hinges
Removable panel—window
Tension straps under main tunnel
Auxiliary tunnel
Position IV
Position I
Removable panel—scientific airlock
Foldout panels (extended)
Prelaunch access panel
Ordnance plate (severed)
Preload trunnions

The meteoroid shield, above. The overlapped ends were joined by trunnion bolts, used during rigging to tighten the shield against the workshop. The extra circumference required when the shield was deployed was provided by foldout panels, released by ordnance. At right, one of the 16 torsion rods and swing links that moved the shield (at top, darker) out to the deployed position. The lower end of the auxiliary tunnel, which would figure in the launch accident, is visible. MSFC 028356.

with an ultrasonic device: 62% of the surface was touching the workshop. The workshop was then pressurized and the contact areas again mapped: 95% of the two surfaces were in contact. Since the pressure differential between the workshop and the shield would be substantially higher during flight, Huntsville accepted the rigging.[45]

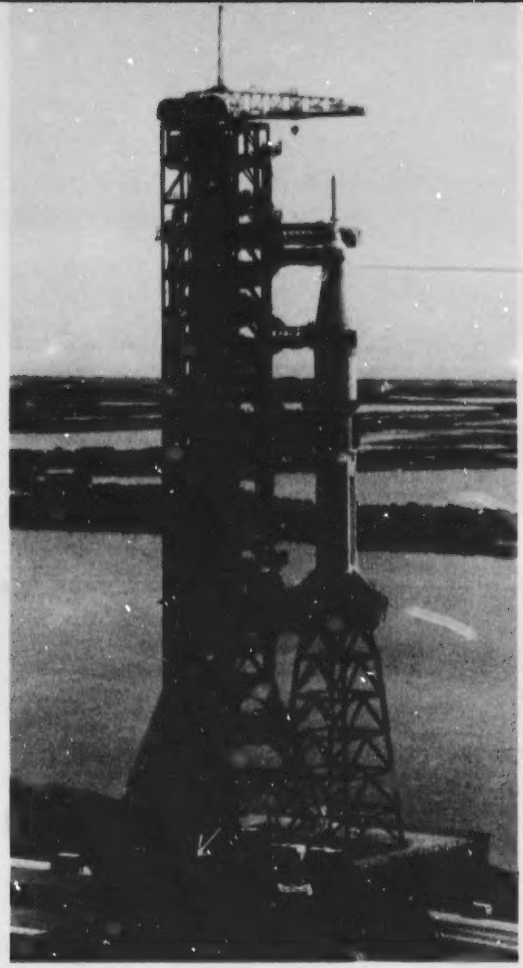
Once in orbit the shield would be deployed to stand 13 centimeters off the workshop, and verification of deployment added to the launch team's troubles. On the first try, two latches that helped fasten the shield in place during flight failed to engage. Three of 16 torsion rods used to rotate the shield outward appeared overtorqued, and 1 was subsequently replaced. On the second test, the upper latch failed again. As the lower latch was sufficient to retain the shield, Huntsville accepted the condition. The final rigging for flight began in late October, several weeks behind schedule.[46]

Tests of the workshop launch vehicle began in early November, in parallel with checkout of the workshop. In mid-November, the two solar arrays—their wings folded in—were mounted to the workshop. Tests on the refrigeration system were completed by Thanksgiving and on the waste-management system by Christmas. The Saturn IB was rolled out on 9 January.[47]

The airlock and docking adapter arrived on 6 October, the last major items to reach the launch center. During the next four months, all modules were examined exhaustively in the Operations and Checkout Building. Testing of the telescope mount uncovered few major problems, and by mid-January the Huntsville team had attached its thermal shield and solar arrays. Other hardware proved more troublesome, in particular the earth-resource experiments, which had been among the last added to the Skylab program. As late as January, Martin Marietta was reporting problems with signal conditioners, videotape recorders, and the heat control for the window of the multispectral camera.[48]

End-to-end tests on the earth-resource instruments proved particularly frustrating. In these exercises, technicians simulated subject matter for the cameras to record. After the equipment ran through a typical operation, video tapes were removed and the results checked against the input. Repeatedly, significant fractions of the data were not recorded. Eventually the Martin team, at the suggestion of a KSC employee, tried two rudimentary procedures—cable wiggling and pin probing—that were outlawed at the Denver plant. During a test, a technician wiggled each cable at a specific time. Comparison of the movement with data output identified half a dozen erratic channels. A subsequent probing of cable connector pins revealed several defective joints. With new connectors, the instruments performed satisfactorily.[49]

The problems with the earth-resource experiments were typical of Skylab. During eight months of prelaunch operations, one-third of the



The Apollo spacecraft and Saturn IB launch vehicle that would carry the second crew to Skylab, *shown moving to the pad 11 June 1973.* 108-KSC-73P-369.

hardware required repairs in place; another one-fifth caused mechanical problems during installation. More important, 61% of the experiments had to be removed from *Skylab* because of test failures or late design changes, greatly increasing the checkout time. Besides the hours spent removing and reinstalling hardware, the changes entailed retesting of all interfaces. The experiment project officer at KSC concluded that the experience "did not support the theory that as industry gains experience in building and testing space hardware the product will get better and there will be fewer failures at the launch site." He noted that much of *Skylab*'s hardware was pushing the state of the art and was therefore highly susceptible to test failures and design changes. From the test results, he estimated that about one-third of *Skylab*'s experiments would have failed in space without the launch checkout.[50]

FROM CERTIFICATION REVIEW TO LIFTOFF

Program officials gathered at Merritt Island on 19 January 1973 for the design certification review of the launch complex. The review was the last of a series dating back to June 1972 in which the manned spaceflight management council had examined Skylab hardware, experiments, and mission operations (p. 122). The meeting at KSC focused on single-point failures,* such as the mobile service structure, and those elements of the launch complex that had undergone significant change from Apollo operations. No major shortcomings emerged from the review; at its close, KSC and Marshall were asked to complete action in a dozen areas, among them dynamic analysis of the pedestal and a review of previous IB launch problems.[51]

The trip also gave Schneider a first-hand look at the lagging operation. Testing on the airlock-docking adapter had fallen four days behind in early January, raising doubts that the launch team could stack the modules on the Saturn V by the 19th. Postponement became a foregone conclusion a week before the deadline, when the launch team had to remove the control and display panel from the earth-resource experiments. The test office, faced with another week's delay, rescheduled the mating for the 29th. Upon reviewing the various test problems, Schneider concluded that the entire schedule should slip at least two weeks. The lost time might be made up, but further delays were just as likely. In announcing the decision, a NASA spokesman noted that "the current posture cannot be attributed to any one item, but is a result of the first-time testing of the modules and the many experiments." Tentative dates of 14 and 15 May were set for the first launches. Firm dates were to be established in late March.[52]

Fewer problems cropped up during the next two months. An integrated systems test begun on 9 February represented the first test of the workshop and its launch vehicle as a unit. The 10-day exercise went smoothly except for minor problems in the refrigeration system, most of them involving ground support equipment. On 20 February, Rockwell brought the Apollo command and service modules to the assembly building for mating with the Saturn IB. The stay was brief; within a week that vehicle was on the pad. March was a month of testing and loading. On the 7th, Martin Marietta finished the last of four simulated passes with the earth-resource cameras. Two weeks later the entire launch team ran through a simulated countdown and liftoff of the workshop during the flight readiness test, the last major milestone before the vehicle left the assembly building. The exercise continued four more days, testing the

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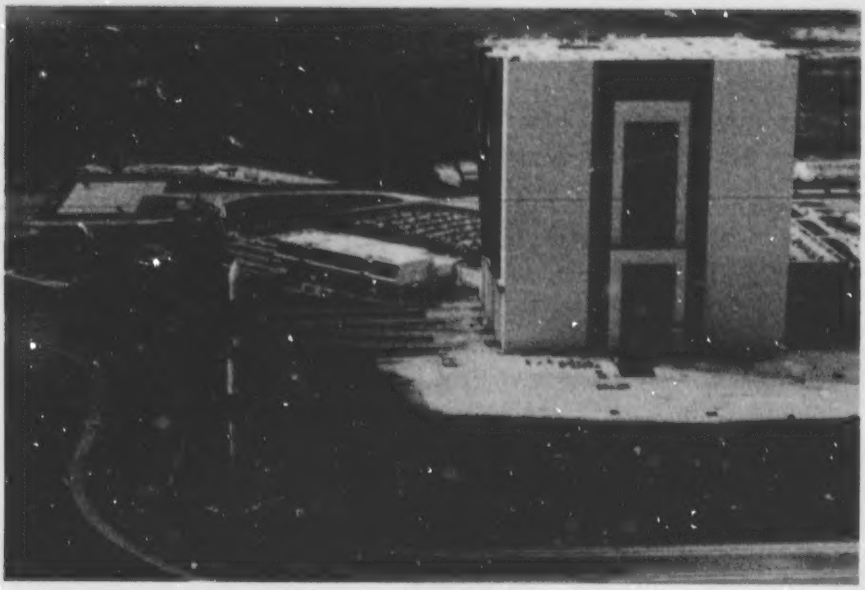
* Single-point failures were those that would terminate the operation because there was no backup for the faulty equipment.



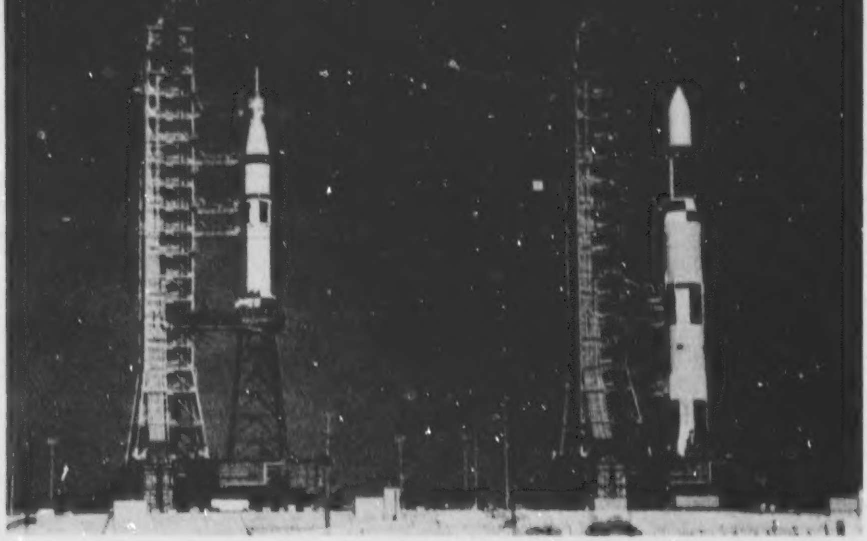
Skylab *and the last Saturn V to be launched being carried by a crawler-transporter from the Vehicle Assembly Building (right) to the pad, 16 April 1973.* 108-KSC-73P-240.

initial workshop operations. At the same time, technicians were loading provisions; by the end of the month, that job was 70% complete.[53]

During the final two weeks in the assembly building, the launch team conducted a series of crew compartment fit and function tests, a final inspection ensuring that everything was in its place. The test office report of 12 April concluded, "the internal OWS is closed out for flight." Final actions in the high bay included the installation of the payload shroud, a relatively simple shell that covered the telescope mount during launch. The ordnance used to separate the stages or to destroy an errant vehicle was added on the 14th, and the workshop rolled out two days later.[54]

On the pad, first order of business was to connect and test various support systems: fuel, water, electricity, environmental control, and high-pressure gas lines. On the 25th, the launch team began the countdown demonstration test, a dress rehearsal of the final week. For 10 years this exercise had climaxed Saturn prelaunch operations; on Skylab, however, it was even more important as a test of integrated operations for two space vehicles. Months of planning paid off when the dual countdown proceeded without a major hitch. Following simulated liftoffs on 2-3 May, fuel tanks were drained and insulation was inspected. Then a second terminal count began for the Saturn IB-Apollo—a dry run with the crew aboard.[55]

Program officials awaited the launch of the workshop with mixed feelings. There was pride and a sense of relief that, after long years of



Deliberate double exposure permits comparison of the first two space vehicles to be launched in the Skylab program; they were actually 3 km apart. On the left, perched on the milkstool, is the Saturn IB that would loft the first crew. On the right, the Saturn V's third (upper) stage has been replaced by Skylab. 108-KSC-73PC-199.

work, the laboratory, its launch vehicle, and launch complex 39 were ready. There was also apprehension: so many things could go wrong—and had, at various times in the past. On most programs the maiden flight was only the first of several launches; a failure meant delay, sometimes costly delay, but it did not spell the end. Skylab's success, however, depended largely on the outcome of its initial launch. If something went wrong, it was doubtful that Congress would provide the $250 million necessary to try a second time.

The weather provided the suspense for the final 10 days of launch operations. After a heavy rain on 4 May, workmen discovered that the payload shroud leaked, but attempts to seal it were delayed by high winds and more rain. On the 9th, the first day of the final count, lightning struck the mobile launcher, forcing a hurried retest of vehicle systems. Fortunately the thunderstorms abated during the rest of the week, and the final countdown proceeded without a major hitch. Just before liftoff, Martin Marietta technicians rectified an oversight—attaching a metal United States flag to the docking adapter.[56]

At 1:30 p.m. on 14 May, the workshop cleared the launch tower and mission control passed from KSC to JSC.*

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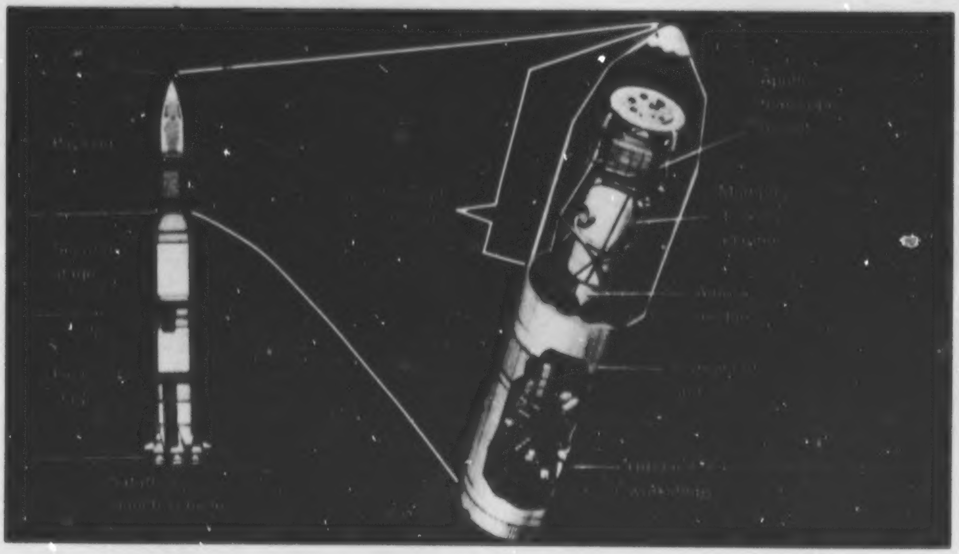
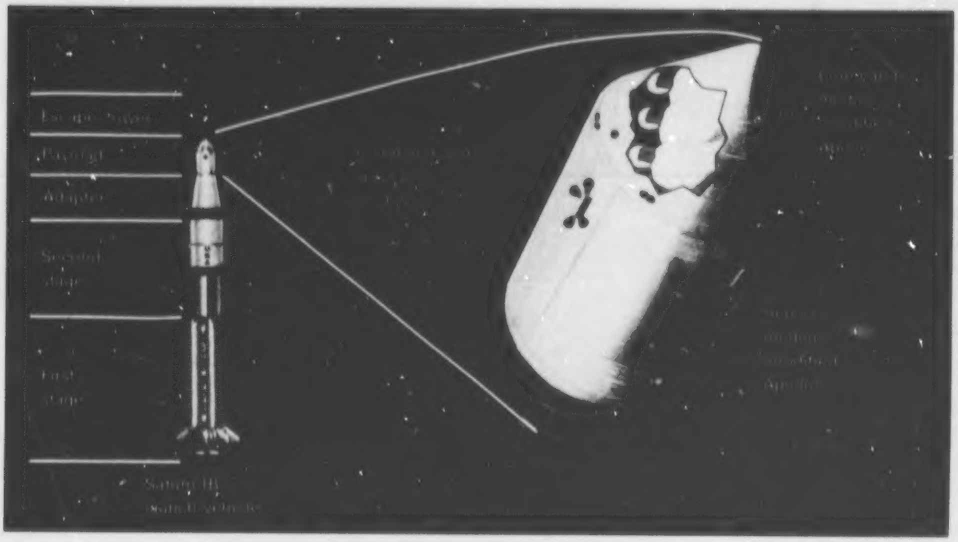
* The Manned Spacecraft Center, Houston, was renamed the Johnson Space Center on 17 February 1973.


Payload
Second stage
Apollo

Launch configuration. Above, the unmanned Skylab. S-72-1768-S. *Below, an Apollo with crew.* S-72-1794-S.


Escape tower
Payload
Adapter
Second stage
First stage
Saturn IB launch vehicle
Apollo

Part III

The Missions and Results, 1973–1979

Skylab's debut as the sustaining mission for American manned spaceflight was a near-disaster. One minute into the flight the meteoroid shield—which also served as the primary means of thermal control—ripped away, leaving the workshop exposed to searing solar heat and in the process disabling its solar panels. For two hectic weeks engineers worked to devise ways to repair the damage while flight controllers maneuvered the spacecraft to minimize damage from excessive heat. Their ingenuity and perseverance saved the $2.5 billion program, and the manned missions went off with surprisingly little dislocation.

Experimenters learned much from the Skylab program. So did crews and flight planners: what they learned was something about the infinite variability of man. The resourceful "can-do" first crew was succeeded by a hard-driving group of overachievers and in turn by the methodical, sometimes stubborn third crew. No one could reasonably fault the performance of any of these crews, but once more it was impressed on everyone in the program that astronauts are not interchangeable modules.

The scientific productivity of Skylab was impressive, almost overloading some of the investigators with data. So too was the physical adaptation of the astronauts to orbital flight. After Skylab, prolonged weightlessness would no longer hang as a threat over lengthy missions. The third crew eclipsed all existing flight-duration records with an 84-day mission whose length would not be surpassed for four years.

The derelict workshop stayed aloft for five years after the last mission, while manned spaceflight languished. Technical and financial problems in Shuttle, the next manned program, pushed its first flight further into the future day by day. Since NASA had intended to use Shuttle to boost *Skylab* into a higher, longer-lived orbit, the workshop was doomed to an uncontrolled reentry into the atmosphere, with consequences no one could predict. For three months in 1979 *Skylab* was in the headlines as it had not been since the success of the first manned mission. But in spite of sometimes near-hysterical public anticipation of the workshop's reentry, it came to the end of its road with a few spectacular but harmless fireworks.

The last section of this book deals with the launch accident, the missions, the results of the program, and *Skylab*'s end.

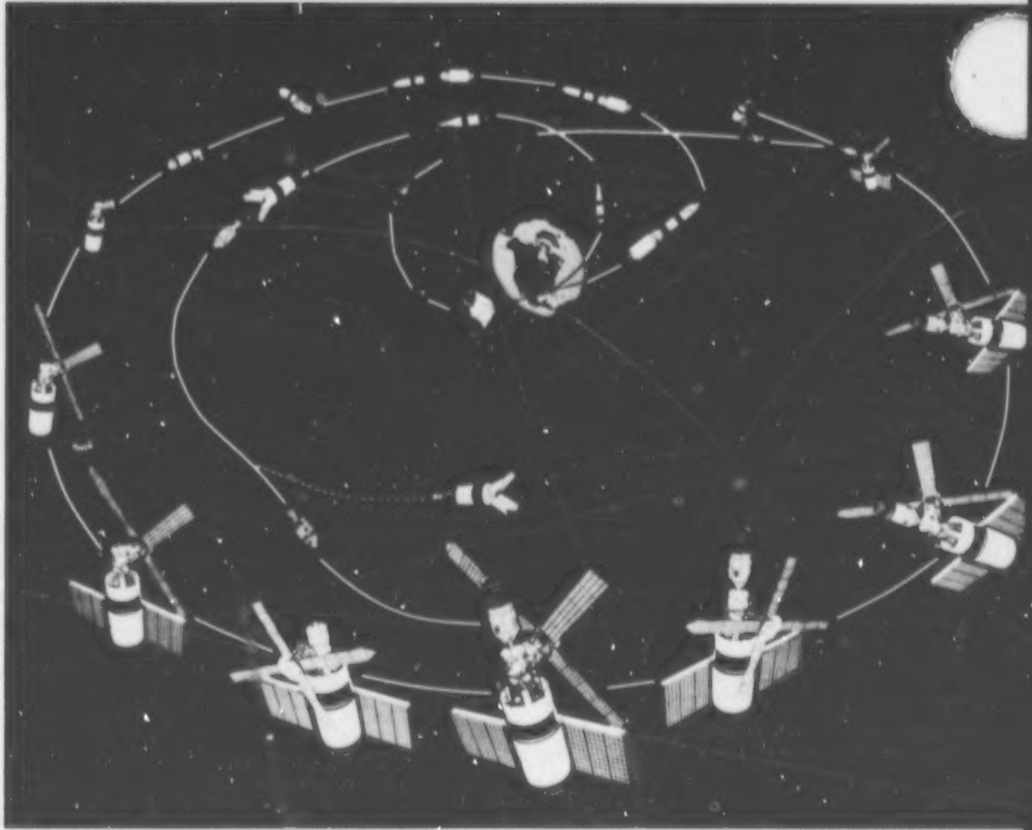
14

Saving Skylab

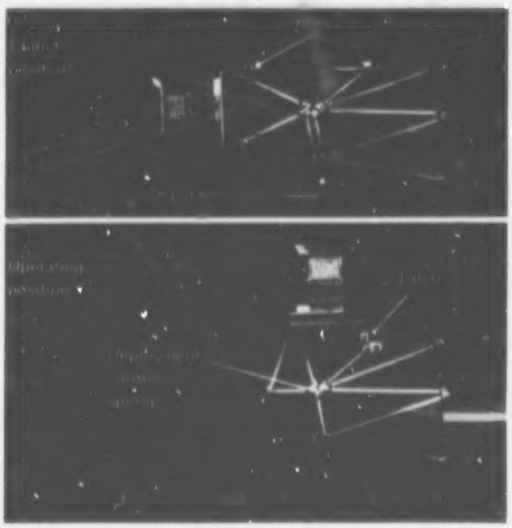
The Saturn V performed its final mission in style, and 10 minutes after liftoff on 14 May 1973 *Skylab* was in its planned orbit, 436 km above the earth. During the next half hour a series of commands from the instrument unit would bring the laboratory to life. First a radiator cover was jettisoned so that the refrigerators could be switched on. Next the four sections of the payload shroud peeled away; Skylab officials, recalling the failure of a similar cover on *Gemini 9*, breathed a sigh of relief. With deployment of the telescope mount from the forward end of the stack to its flight position astride the docking adapter 16 minutes into the flight, *Skylab* passed a crucial hurdle. The move cleared the path for the Apollo spacecraft to reach its docking port. Within minutes the telescope mount's four solar wings, resembling the sails of a Dutch windmill, opened. Meantime, the spaceship had assumed a solar inertial attitude, its long axis in the plane of the orbit and the telescope mount pointing toward the sun. Thus far there had been only one curious indication, a report from Houston that the meteoroid shield had deployed prematurely. When nothing more was heard, officials at the launch site dismissed the indication as a false telemetry signal. After the telescope mount had moved into its proper position, there was time to relax while awaiting deployment of the workshop's solar arrays.[1]

THE ACCIDENT

The relaxation was short lived. About half an hour after liftoff, Flight Director Donald Puddy in Houston reported erratic signals from both the meteoroid shield and the workshop solar arrays. The solar wings were scheduled to deploy 41 minutes after launch, when *Skylab* had passed beyond the range of the station at Madrid. Tension mounted as officials listened for news from the tracking station at Carnarvon, Australia. The information was confusing. One telemetry signal indicated that the array had released for deployment but was not fully extended, while temperature signals suggested that both wings were gone, a conclusion reinforced by the absence of voltage signals. The failure of backup com-



Mission sequence for the first two Skylab missions. MSFC-72-SL 7200-130C.



Deployment of the Apollo telescope mount, uncovering the docking port through which the crew would enter. ML71-5285.

mands from both Goldstone, California, and Madrid seemed to confirm the worst fears. The solar panels were the main topic of discussion at the postlaunch briefing at Kennedy.[2]

By late afternoon, it appeared that *Skylab* had at least two major problems. If the workshop solar panels were indeed gone, *Skylab* had lost nearly half of its electrical power. The workshop and ATM array each provided about 5 kw of usable power. Apollo fuel cells could produce an additional 1.2 kw for 20 days; after that the command-service module would draw electricity from *Skylab*. The system had been designed with power to spare; even without the workshop panels, officials believed an adequate mission was possible until Apollo's fuel cells ran dry. Then the crew would be forced to curtail most experiments for the last week. The second and third crews would be hampered for much longer periods.[3]

The power shortage drew most attention at an evening press conference; little was said about an even more serious problem, the apparent loss of the micrometeoroid shield. No one was particularly worried about damage from a meteoroid strike, since the chances of a hit were slim.* But the shield's secondary function, thermal control, loomed large in the aftermath of the launch. The shield had been designed to keep the workshop on the cool side of the comfort zone, heating being easier than cooling. The outside of the shield was a black-and-white pattern designed to absorb the desired amount of heat. The inside of the shield and the outside of the workshop were covered with gold foil, which regulated the flow of heat between the two. It was an admirable system as long as the shield stayed in place. Without it, the gold coating on the workshop would rapidly absorb excessive heat, making the interior uninhabitable.[4]

The shield had failed to deploy at the scheduled time and subsequent ground commands had no effect. While officials were debating further action, Saturn engineers discovered flight data indicating an anomalous lateral acceleration about a minute after liftoff. The data, coming just before the space vehicle reached its maximum dynamic pressure, suggested some structural failure. A short time later, workshop temperatures began rising, strong evidence that the shield was gone. Within a few hours, readings on many of the outside sensors exceeded 82° C, the maximum scale reading. Internal temperatures moved above 38° C. Working from the thermal model, Huntsville engineers figured that workshop temperatures would go as high as 77° C internally and 165° C on the outside, endangering food, film, perhaps even the structure itself. Mission Control therefore began maneuvering the exposed area out of direct sunlight, and some cooling occurred.[5]

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* The shield was added to the wet-workshop design in March 1967 when there was still much uncertainty about meteoroid hazards (p. 55). NASA subsequently placed the probability of a strike at about 1 in 100. A puncture would not necessarily end the mission, as the crew could patch holes up to 5 mm and then replenish the workshop's atmosphere.

A bleak picture confronted the Skylab team the evening of launch. Besides the overheating and the lack of power, the attitude-control system had problems. Responses from rate gyroscopes were not averaging properly, and the initial maneuvers had expended excessive amounts of nitrogen gas. No doubt engineers wished they could bring *Skylab* back for repairs. This was out of the question, of course. The chances of repairing it in space looked unpromising, but the attempt had to be made.[6]

The first decision was to delay the launch of the crew by five days. Huntsville began a series of analytical studies to predict likely temperatures in the workshop and assess their impact. Both Huntsville and Houston started investigating ways of deploying a thermal shield. At the same time, contractors and other NASA centers were encouraged to pursue independent studies.[7]

At Marshall, Center Director Rocco Petrone moved with characteristic vigor, giving carte blanche to a special task force under the direction of the deputy directors of the Astronautics and Astrionics Laboratories: "Whatever you need at the center is yours." The team operated from the Huntsville Operations Support Center, with personnel largely drawn from the mission support groups. Marshall's laboratories and contractors' plant provided additional help. Computer time was soon in short supply. Eventually much of the work was done on Martin computers in Denver, and sometimes procurement had to search elsewhere.[8]

The accident drastically altered activities within Huntsville's operations center. A normal 40-hour week had been planned for operations personnel, with a skeleton crew on duty the remainder of the time. Facing an emergency of undetermined length, officials quickly established an around-the-clock schedule, reinforcing the operations team with Skylab design engineers. The support groups directly affected by the accident (electrical power systems, attitude control, and environmental control) doubled in size, while overall numbers at the operations center increased from 400 to 600.[9]

At first, Eugene Kranz, chief of JSC's Flight Control Division, tried to operate with his four flight-control teams, having each team work specific problems when not manning the consoles, so that individuals who worked out plans could then implement them. By the 15th, however, the scheme had become unworkable. Too many things required investigation, and the major problems demanded continuous attention. Two teams were directed to man the consoles around the clock, while the other two supported contingency planning: altering the flight plan and activation checklist, supporting development of a sunshade, and reducing power requirements of the workshop.[10]

If Huntsville and Houston bore the heaviest responsibility, the entire Skylab team was involved. From Huntington Beach to Cape Canaveral, workdays of 16–18 hours became normal, and people lost track of time. Tempers remained remarkably calm despite the long hours. Relations between Marshall and JSC were excellent, a condition that both sides attributed to the close working ties that had grown up during Skylab's design and development phases. There was healthy competition between groups developing sunshades, but in looking back on the time, participants most often recalled the teamwork and the tremendous amount of work accomplished in such a short time. Huntsville officials referred to the period as "the 11 years in May."[11]

MANEUVERING FOR MINIMUM HEAT, MAXIMUM POWER

The electrical power situation, while bothersome, was not an immediate threat. But the workshop's temperature had to be lowered fast. Separately, neither problem seemed insurmountable; together the loss of the solar panels and meteoroid shield posed a dilemma, for anything that reduced the effect of one malfunction increased the effects of the other. To produce electricity, *Skylab* needed to remain in a solar inertial attitude, with the sun's rays perpendicular to the solar panels, but this position exposed the full length of the workshop. For a time Mission Control pointed the forward end directly at the sun, which lowered temperatures somewhat but also reduced power generation. Experiments with various attitudes showed the best compromise to be pitched up about 45° toward the sun. During the daylight portion of each orbit enough sunshine struck the solar panels to charge the batteries for the next period of darkness, and internal temperatures stabilized near 42°C.[12]

The search for a compromise attitude was complicated by steering problems. Nine rate gyroscopes served as the basic sensors for attitude control, measuring the rate of rotation around three axes. Several gyroscopes overheated the first day, producing off-scale readings and causing the flight controllers to discontinue the practice of averaging the information from two gyroscopes. Fortunately, at least one gyroscope in each axis worked satisfactorily. The gyros accumulated excessive errors, and because the errors were erratic, ground controllers could not compensate for them. During the first few weeks, the attitude-control team waged a constant battle to predict the movement of the rate gyroscopes. The problem was compounded, however, when *Skylab* left the solar inertial plane. Random errors sent spurious signals to the control-moment gyroscopes, frequently causing them to reach saturation (p. 172). Desaturation required a daylight pass in the solar inertial attitude. To reduce the amount of maneuvering required, Mission Control worked out some rough-and-ready substitute procedures: measuring roll attitude by reading temperatures on opposite sides of the workshop, determining pitch angle by the electrical output of the solar wings, and calculating *Skylab*'s momentum to determine if it was in the correct orbital plane.[13]

All these unscheduled manuevers used up large amounts of attitude-control propellant, and while there were possible solutions to the other malfunctions, the gas could not be replaced. Due to favorable launch conditions, *Skylab* had lifted off with an excess supply, but in the first three days the compressed nitrogen that powered the attitude-control thrusters was expended at an alarming rate. By 17 May, 23% of it was gone, twice the amount expected. The situation improved as flight controllers became more adept at maneuvering the workshop. Though the expenditure of nitrogen remained too high, the rate could be tolerated until the first crew was launched. On the 17th, that launch was delayed another five days.[14]

Ironically, while much of the workshop suffered from overheating, the airlock was too cold, dropping below 4°C on the 18th. The suit umbilical system located in the airlock used water to transfer heat from the astronauts' suits during extravehicular activity. Despite attempts to warm the airlock with heaters, its temperature continued to drop, approaching freezing on the 21st. If a line in the umbilical system froze, it might crack the heat exchanger at the junction with the airlock's primary coolant loop. On the 20th, flight controllers had rolled the vehicle a few degrees to expose the airlock to more sunlight. When there was no significant change in temperature, *Skylab*'s pitch was decreased to 40°. On the following day, the workshop was rolled to place the water loops under direct sunlight for one pass. These maneuvers warmed the airlock and produced more electricity, but sent workshop temperatures up as well. By the end of the 21st readings approached 54°C. Flight controllers juggled *Skylab* for the rest of the second week, trying to keep temperatures and power within safe limits. The stable condition expected at the end of the first week eluded them, but at least they prevented serious damage to the vehicle.[15]

Even with the workshop's solar array gone, there was enough power to meet *Skylab*'s needs until the crew arrived—if the ship remained perpendicular to the sun's rays. When sunlight struck the solar panels at less than a 90° angle, however, production decreased sharply. The estimated power requirement for the unmanned *Skylab* was 4.5 kw, a few hundred watts below the ATM power system's maximum output. When it became apparent that maneuvers were essential, engineers turned off heaters and transmitters, reducing requirements to 3 kw. This proved sufficient until the second week, when high-angle maneuvers dropped *Skylab*'s electrical output below that level. On the 24th, 8 of the ATM's 18 batteries stopped working because of excessive electrical demands. Returning the workshop to the solar inertial revived only 7 batteries. The loss pointed up the danger of further high-angle maneuvers.[16]

ASSESSING THE HEAT'S EFFECT

The rapid buildup of heat raised doubts about *Skylab*'s provisions. The day after launch, controllers began plans to restock the larders, assuming that the high temperatures would probably ruin all nonfrozen foods. Over in the food laboratories, however, tests conducted before launch had indicated that the canned food could withstand 54°C temperatures for at least two weeks and the dehydrated items would last even longer. New tests were started to confirm the earlier findings, baking one lot of food at 54° and a second batch at the temperature of the workshop's food locker. Periodic sampling indicated that the heat was not altering the food's mineral content or taste. To be on the safe side, the crew was given a quick course in food inspection. On the 22d Houston officials concluded that the food was all right, and plans to restock the workshop were dropped.[17]

The initial prognosis on *Skylab*'s medical supplies was also pessimistic; it was thought that half of the 62 medications aboard the workshop might be ruined. During the following week, Houston's medical team pared down the resupply list, relying on heat tests and information from pharmaceutical companies. At the same time, Huntsville officials debated the condition of film aboard *Skylab*. While the film for the solar telescopes was out of harm's way in the docking adapter, that for earth-resource cameras and other experiments was stored in workshop vaults. The problem was one of dryness as well as heat—emulsion on the film would dry out in the low humidity. Salt packs placed in the vaults to provide moisture were not expected to last more than 4 days. Kodak engineers believed the crew could restore the film by rehumidifying the vaults, but that might take up to 20 days. Accordingly, plans were made to carry additional film on the Apollo spacecraft.[18]

During the early rise in temperature—to perhaps 150°C at some points on the workshop's exterior—Huntsville engineers feared for *Skylab*'s structural integrity, but the spacecraft was pressurized without incident.[19] A related problem involved the possible release of toxic gases into the workshop. The aluminum wall of the S-IVB tank was insulated on the inside with polyurethane foam. Well suited for temperatures several hundred degrees below zero, the material at 150°C could give off carbon monoxide, hydrogen cyanide, and toluene diisocyanate. The last item was the most dangerous, lethal in small concentrations. Chemical experts from industry and the academic world considered the hazard a long shot and McDonnell Douglas tests indicated that the concentration of toxic gas in the workshop's large volume would not be dangerous. Nevertheless, the workshop was vented and repressurized four times. The crew would wear gas masks and sample the air upon first entering.[20]

DEVISING A SUNSHADE

The *Skylab* maneuvers were an attempt to buy time until some way was found to shade the workshop. Chances of finding a solution were reasonably good, certainly better than the odds given by many newsmen. For one thing, not all of the exposed surface required protection; covering part of the area facing the sun would bring temperatures within satisfactory limits. Second, a shade would not require rigid tie-downs or strong material since there is no wind in space. But a solution had to be found quickly, before the workshop deteriorated beyond recovery. In the week after the accident, Skylab officials examined scores of ideas, ranging from spray paint and wallpaper to balloons, window curtains, and extensible metal panels. Of the various proposals, 10 seemed promising enough to carry through design and at least partial development.[21]

Huntsville officials began considering a replacement for the meteoroid shield a few hours after launch. Some of the early ideas were rather farfetched, but no suggestion was ignored if its "package was light and the deployment relatively simple." Several concepts were discarded after the first review. The astronauts ruled out use of the astronaut maneuvering equipment, experimental gear in which the crew had little confidence. The idea of deploying a weather balloon through the scientific airlock was opposed by thermal engineers, who feared it might reflect enough heat to melt solder joints on the ATM solar panels; they preferred a flat shade with some distance between it and the workshop wall. A similar winnowing of ideas occurred in Houston when Max Faget's engineering directorate met on launch night to brainstorm the problem. After debating a number of suggestions, staff members were assigned specific concepts for further study. Next day paint and wallpaper were eliminated as possible solutions. While spray paint worked surprisingly well in a vacuum chamber test, it posed serious logistical problems and a threat of contamination. Wallpaper was ruled out because of uncertainty about the condition of the workshop's exterior.[22]

From the initial discussions, three promising solutions emerged: extending a shade from a long pole attached to the telescope mount, deploying a shade from the maneuvering Apollo spacecraft, or extending a device through the scientific airlock on the workshop's solar side. The extravehicular activity required by the first option was a drawback since NASA liked to train extensively for such operations. In its favor, the crew had practiced extravehicular work on the telescope mount; and if they had a portable foot restraint, astronauts could face the exposed area without difficulty. A shade deployed from the spacecraft offered the earliest repair and the least complex design. These advantages were offset by the difficulty of flying around the workshop. The scientific airlock provided the easiest operation. Astronauts could extend the shade from inside the workshop using a procedure already prepared for an experiment. The problem was to design a device that would fit through an opening 20 centimeters square and then expand to cover an area 7 meters square.[23]

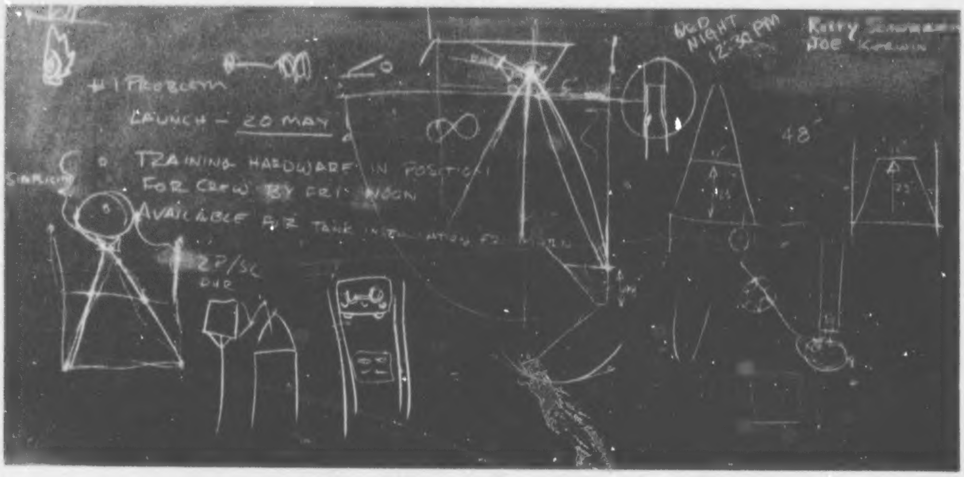
Faget's group at JSC concentrated on rigging a shade from the

Apollo spacecraft, since this seemed to have the best chance of meeting a 20 May launch date. Standing in the Apollo hatch, an astronaut would attach the shade at the aft end of the workshop. The spacecraft would move laterally to another point on the aft end, where he would secure a second corner of the shade. The CSM pilot would then slowly maneuver the spacecraft toward *Skylab*'s forward end, allowing the shade to play out. At the telescope mount, the astronaut would make a third attachment. This shade was soon called the SEVA sail, for Standup Extravehicular Activity.[24]

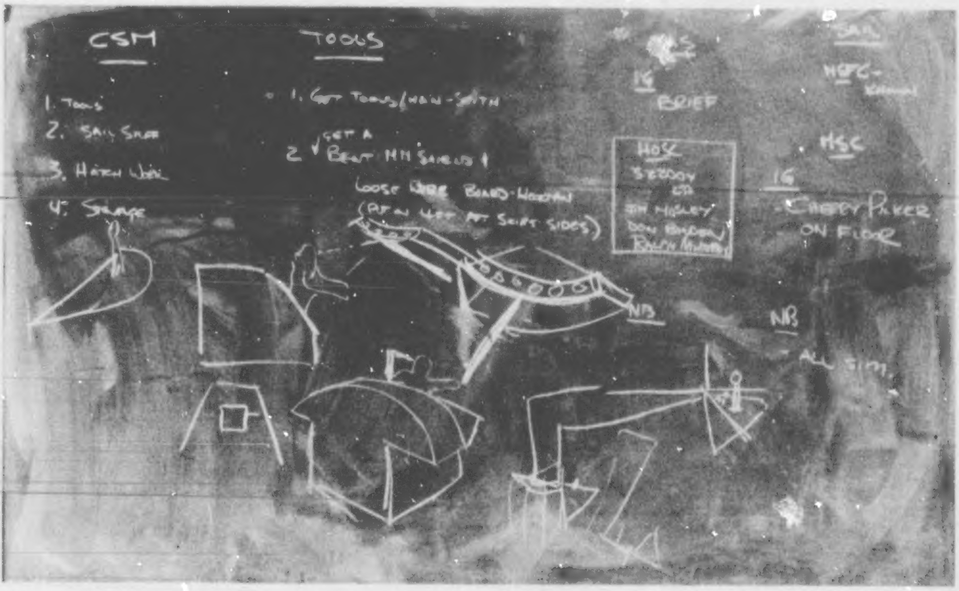
Responsibility for the SEVA sail fell to Caldwell Johnson, chief of the spacecraft design division. He organized a development team and worked in the centrifuge building; for 10 days the group felt like goldfish in a bowl, as public tours to the centrifuge observed their activity from a mezzanine. Seamstresses stitched the orange material, parachute packers folded the sail for proper deployment, and design engineers attended to the various fasteners. Probably the biggest obstacle was getting exact data on *Skylab*, since some drawings were not current. In one or two instances, the engineers relied on photographs provided by McDonnell Douglas. Johnson faced an additional problem—warding off suggestions from other NASA officials, whose good intentions might have improved the design at the expense of the deadline. In spite of minor delays, the SEVA sail made rapid progress. At the Management Council meeting on the 16th, it was tentatively chosen as the first shade for deployment.[25]

Opinion at JSC inclined against sending astronauts outside *Skylab*; Gemini's extravehicular troubles were well remembered. At Marshall, on the other hand, EVA from the telescope mount was preferred, largely because of fears that debris might block the scientific airlock. On the evening of the launch, Huntsville engineers began designing a sunshade that looked like a window blind. Working steadily through the night, the group completed the design on the 15th and immediately started fabrication. Testing started the following evening at the neutral-buoyancy simulator. Russell Schweickart, commander of the backup crew, and Joe Kerwin, scientist-pilot of the prime crew, had flown from Houston to test several devices and determine how much an astronaut could see from the telescope mount. They entered the tank amid a circus atmosphere, newsmen peering through floodlights to watch the underwater activity. Before the work ended, Huntsville engineers concluded that they needed another design.[26]

Schweickart and Kerwin changed from their tank suits and joined 75 Marshall engineers for a debriefing. The astronauts were still in quarantine, and the blue masks worn by the other participants gave the appearance of a surgical ward. Schweickart sketched ideas on a blackboard as the discussion proceeded. Simplicity was essential; launch was less than four days away and crew training, transport, and stowage would


#1 PROBLEM
LAUNCH – 20 MAY
TRAINING HARDWARE IN POSITION FOR CREW BY FRI NOON
AVAILABLE AIR TANK
27/SC
WED NIGHT 12:30 PM
Rusty
Joe Kerwin
48°

Blackboards at Marshall Space Flight Center following the skull session that originated the twin-pole sunshade, 16 May 1973. MSFC 040066, 040067.


CSM
1. TOOLS
2. SAIL SHADE
3. HATCH WELL
4. STOWAGE
TOOLS
1. GET TOOLS (HEN-SMITH
2. GET A BEST MH SHIELD
LOOSE WIRE BOARD-HOODMAN
(RT ON LEFT AFT SKIRT SIDES)
16
BRIEF
HOSC
NB
NB
MSFC
HSC
16
CHERRY PICKER ON FLOOR
ALL SIM

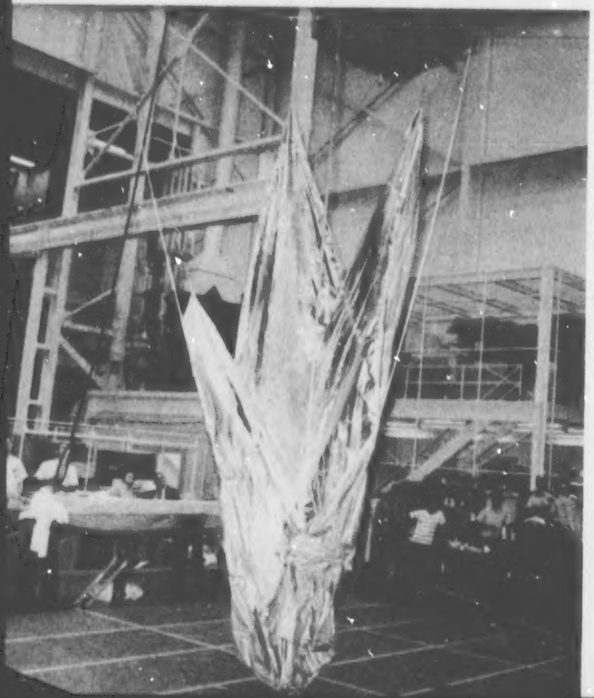
require at least 36 hours. By early morning, the group had settled on a new configuration of two poles, to be cantilevered from the telescope mount. The 17-meter poles would be assembled from 11 smaller sections. A continuous loop of rope would run the length of each pole through eyelets at the far end. After the shade was attached to both ropes, it could be pulled out much as one hoists a flag. The height of the poles above the workshop could be varied if necessary to avoid debris.[27]

While Huntsville proceeded with its twin-pole sail, a Houston team was developing the parasol that would be the first sunshade. Its designer, Jack Kinzler, had not been among the officials initially contacted for ideas. Although his Technical Services Division enjoyed a reputation for building flight items on short order, it was not a part of Houston's R&D engineering force. Kinzler had a practical bent, as well as a personal interest in saving the mission for his close friend and neighbor, Pete Conrad. The morning after the launch he began designing possible solutions. Having stowed many items in the Apollo spacecraft, he was familiar with the weight and size constraints. He was predisposed to use the scientific airlock since it would simplify operations for the crew. He soon hit upon a happy combination of coiled springs and telescoping rods to provide the means of deploying a large cover though a small porthole.[28]

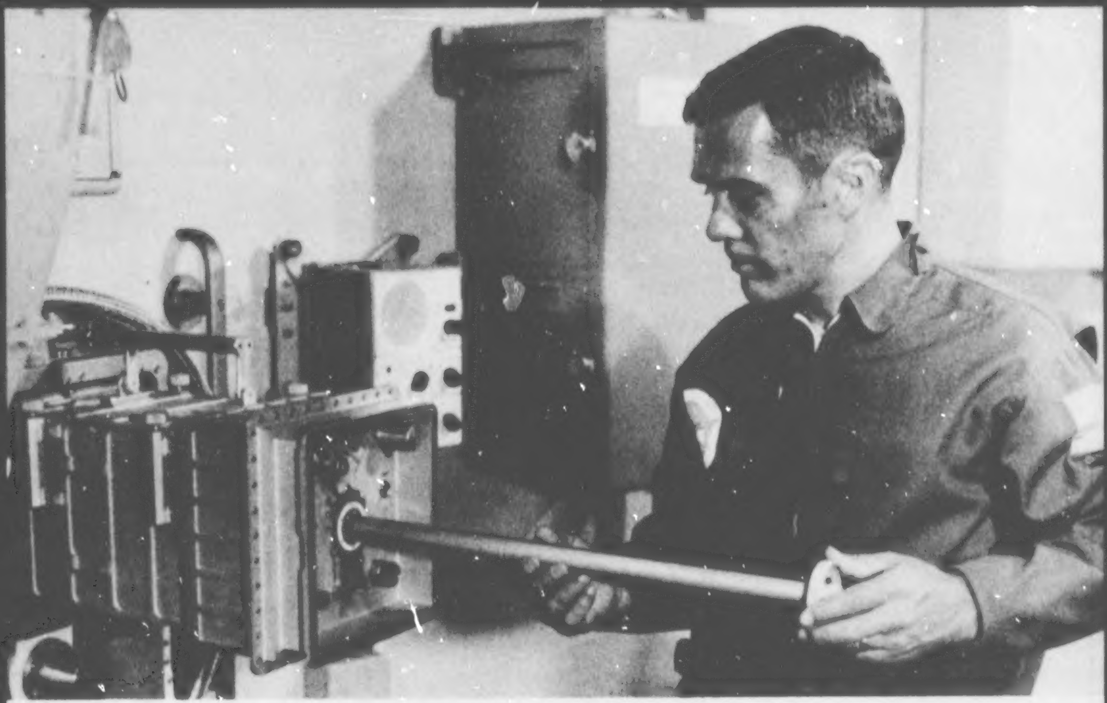
By the 16th, Kinzler's inspiration was taking shape. He attached a parachute canopy to some telescoping fishing rods that were fitted in hub-mounted springs. Springs, poles, and canopy were then stowed in a container roughly the size of the airlock canister. Kinzler deployed the parasol with strings tied to the telescoping rods. As the fishing poles extended and locked in a horizontal position, the attached parachute formed a smooth canopy. Demonstrations quickly convinced Houston management of the concept's merit, and Kinzler was encouraged to continue.[29]

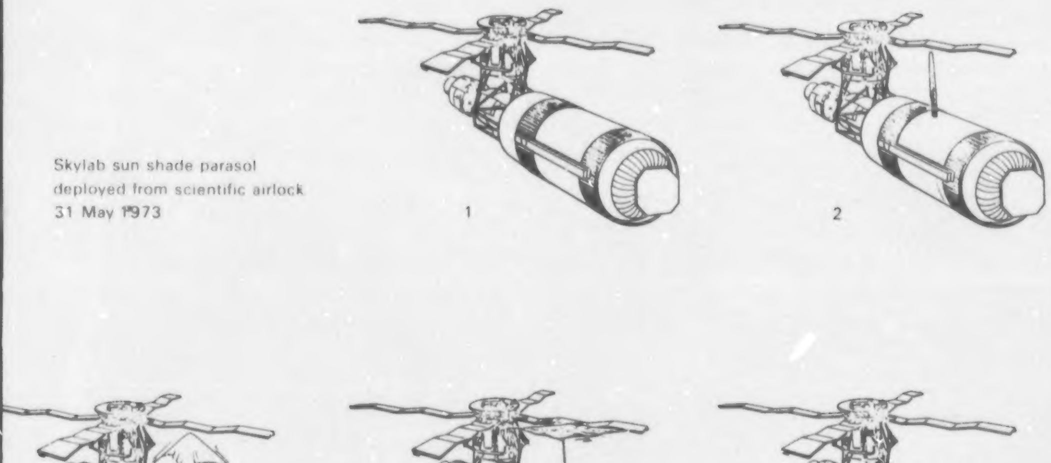
Selection of the prime shade was a major topic of a telephone conference of Skylab officials on the 19th. The decision to delay the crew's launch the second time had eliminated the SEVA sail's principal advantage. Flight controllers had reservations about it anyway—its deployment would cap a rugged 22-hour launch day for the astronauts. Furthermore, the Apollo thrusters might contaminate the telescope mount and its solar panels. Medical representatives favored the parasol, not wanting to chance an EVA early in the mission before the crew was acclimated to space. Deke Slayton stressed that using the scientific airlock was "the most direct approach and the least difficult [operation] for the crew." Schneider believed Huntsville's twin-pole sail had the best chance of success, but Kraft wanted to eliminate it because it was 25 kg overweight. During a second status briefing that night, JSC's director recommended further development of the SEVA sail in case Huntsville's should fail neutral-buoyancy tests. The group approved Kinzler's parasol—Conrad's preference—placing it ahead of the twin-pole sail.[30]

Confident that its twin-pole shade would work in space, the Huntsville group designed it for easy deployment in the neutral-buoyancy tank. As Schweickart recalled, "our real challenge . . . was convincing man-



The parasol sunshade developed at Johnson Space Center. Details of hardware, above, S-73-26374, -26381, and rigging, left, -26389. Packed into a modified experiment canister, the sunshade would be deployed through the scientific airlock, above right. Martin Marietta photo. *The sketches show the steps in deployment, which would result in the sunshade being held close to the workshop wall.*



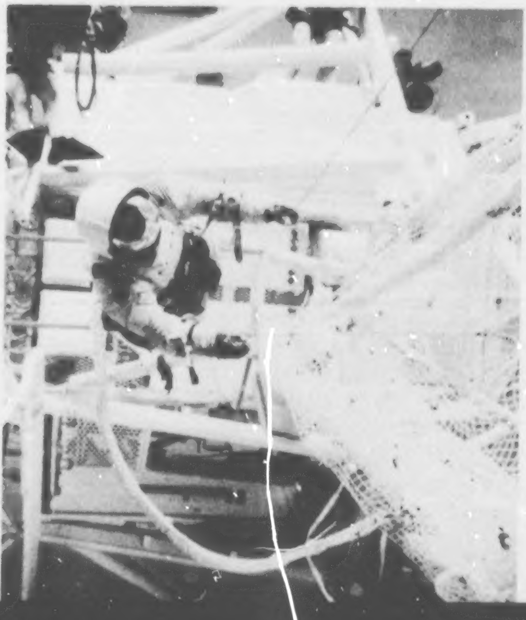


Skylab sun shade parasol
deployed from scientific airlock
31 May 1973

The twin-pole sunshade being made, 22 May 1973. 108-KSC-73P-323.

agement that we could do it." In several instances "we set about designing the equipment [to] look good." In spite of the tight schedule, Marshall observed its traditional steps of design and development, including preliminary and critical design reviews, bench checks, and static and dynamic structural tests. Huntsville aimed at completing its shade by the 22d, when NASA management would review the deployment in the neutral-buoyancy simulator. A tank test on the 18th confirmed the shade's feasibility, but also indicated that the pole sections could separate under stress. After the locking nut was modified, the shade's weight was reduced, and teflon inserts were placed in the eyelets to reduce friction, the dress rehearsal in the tank went off without a hitch.[31]

In Houston, Kinzler's parasol was nearly made over. The fiberglass fishing poles were replaced by stronger aluminum rods, the coiled springs by a "rat-trap" spring. The canopy had to be enlarged when Huntsville's thermal engineers calculated the exact requirements. Perhaps the biggest change involved the shape of the frame. The airlock was found to be



While safety divers look on, Astronaut Jack Lousma erects the twin-pole sunshade over a portion of a workshop mockup in Marshall's water tank, 22 June 1973. For the underwater simulation, nylon netting was used instead of the aluminized fabric that would be used to make the sunshade. He is standing on the telescope mount. 73-H-640.

considerably off center of the area to be shaded. Since there were distinct advantages in packing and deploying a symmetrical frame, Kinzler designed all four arms to the same length, 6.5 meters, letting the rods on two sides extend beyond the off-center canopy.[32]

After the 17th, Director Chris Kraft concentrated most of JSC's resources on the parasol. Faget's engineering division provided design support while Donald Arabian, program operations manager, directed configuration control and testing. Arabian quickly expanded the parasol team beyond Houston, farming out specific requirements to North American and Grumman. During the second week, he and Kinzler supervised development, exercising joint veto power over changes. Both men recall a lot of "engineering after the fact." If something looked like it would work, they built it and designed the details later.[33]

Certain basic criteria governed the selection of shade material, the foremost being its thermal performance. The material also had to be lightweight, compact, deployable, noncontaminating, and stable over a wide range of temperatures. Materials were unacceptable if they tended to retain their stowed configuration when deployed. "What appeared to be a relatively straightforward design problem to some of the enthusiastic shield designers turned out to be a nightmare of complexity when all the . . . design criteria were addressed." A spacesuit material consisting of nylon, mylar, and aluminum was selected. Less than 0.1 mm thick, it met all the criteria but one—nylon had a marked tendency to deteriorate under ultraviolet rays. Deterioration could be reduced by applying thermal paint to the nylon. The paint added considerable thickness to the material—no problem for the SEVA and twin-pole sails, whose containers had room to spare, but the parasol fitted tightly into a small container. Houston canvassed the country for information, finding no precise data on nylon's long-term exposure in a vacuum, partly because NASA had avoided using nylon in space. Before the end of the first week, Houston opted to go without the paint; the second crew could replace the parasol if it deteriorated.[34]

Huntsville had less confidence in the unpainted nylon. Several days after the accident, Robert Schwinghamer's office began testing JSC's shades as part of a program that involved a dozen materials and 49 tests. After 100 hours of solar-vacuum testing, nylon lost half its pull strength. Houston officials were not greatly worried by these results or similar findings at their own center; they believed the inner surface, aluminum, would reflect most of the heat in any case. The Huntsville studies, however, showed a decline in shielding performance as well as strength.[35]

At the design certification review in Huntsville on the 23d, every major aspect of *Skylab*'s problem was covered, with particular emphasis on sunshade candidates and materials testing. Houston's spokesman summed up the case against nylon: although test results varied, all showed the material deteriorating in time under exposure to ultraviolet rays. In executive session, Skylab's top officials agreed to retain the parasol as their first choice but with a protective covering for the nylon. Houston, anticipating such a decision, had selected kapton, an ultraviolet-resistant tape. The twin-pole and SEVA sails, made from the same nylon-reinforced material, would be covered with thermal paint. Langley Research Center was directed to continue work on an inflatable device in the event there should be an unexpected hitch with the parasol.[36]

The decision in Huntsville left JSC less than a day to modify its two shades. Wednesday evening crews began applying kapton to the parasol and spray-painting a SEVA sail. Caldwell Johnson's team quickly ran into problems on the latter; contaminants in the paint required a lengthy straining process, and the oven-drying took longer than expected. By Thursday morning it was uncertain whether the SEVA sail would dry in time for the launch. Parasol modifications proved even more troublesome as the additional bulk of the kapton made stowage difficult and release even harder, raising serious doubts that the shade would work in space. Morale at the Houston center, at a high point a day earlier, plummeted. At a final review at Kennedy, the parasol, with its nylon unprotected, was reconfirmed as the primary device. The educated guess of most materials experts was that the nylon would last at least 28 days. Marshall's twin-pole shade would be deployed later if the parasol showed signs of deterioration.[37]

In Houston, packing the parasol proved difficult, even without the kapton. In its final configuration, the extension rod was recessed more than expected. Kraft noted that the astronauts would have a difficult time connecting the sections of rod. The parasol team agreed to add a 5-cm sleeve. Manufacturing began as the parasol was delivered to Ellington Air Force Base; the new piece followed on a separate flight to the Cape, arriving just before final closeout of the spacecraft.[38]

PLANS TO INCREASE *SKYLAB*'S POWER

NASA's immediate electrical problem was to reduce power requirements; but for the long run, more power had to be provided. The ATM and Apollo electrical systems, though adequate for most of the first mission, would fall far short on the 56-day flights. Schneider put Houston and Huntsville to work on promising concepts. JSC examined a solar-winged module to dock at the side port of the docking adapter; Marshall investigated variations of a portable array. The necessary hardware modifications precluded the use of either by the first crew, but there was a third option. Telemetry suggested that remnants of the meteoroid shield still held one of the two workshop arrays in place. Its release would solve the problem quickly. The debris might be cleared the first day, during a standup EVA from the Apollo hatch. It was just a hope; Schneider told a press conference that "we're not too optimistic." More likely, NASA would have to settle for photographs that would improve the chances of deployment later.[39]

The chief of Marshall's Auxiliary Equipment Section was given the responsibility of developing tools to cut away debris. He started with tree-trimming shears from a Huntsville hardware store and then called the A. B. Chance Company of Centralia, Missouri, maker of tools for power companies. Chance officials agreed to display their complete line of tools in Huntsville the following day. Two items were selected: a cable cutter and a universal tool with prongs for prying and pulling. Both were modified for mounting on a 3-m pole.[40]

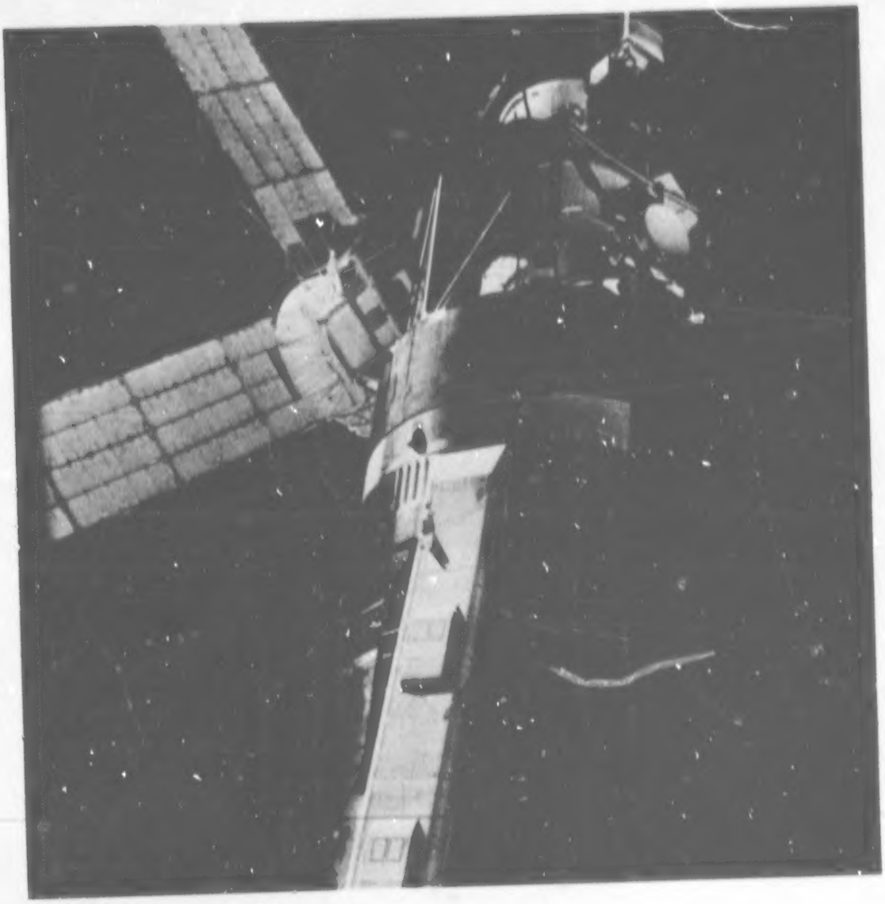
While the tools were under development, Huntsville's Space Simulation Branch prepared a *Skylab* mockup in the neutral-buoyancy tank, complete with loose wires, twisted bolts, and fragments of a meteoroid shield. Close by, supports were installed for a model of the command module, flown in from Houston. NASA officials evaluated the tools on the 21st, and the following day astronaut Paul Weitz practiced freeing a solar array. The tools had already left for Kennedy when the certification review ruled that the pointed tips of the cutters were a hazard. New heads with blunt tips were quickly prepared and the change made at the launch site.[41]

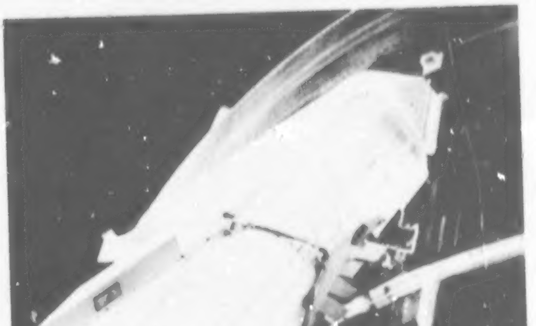
LAUNCH AND DOCKING

Final launch activities were interrupted by a lightning strike on the service structure's mast that knocked a spacecraft gyroscope off line. The guidance and navigation system was quickly retested and the count resumed. The schedule was altered when the parasol's delivery became problematic; propellants were loaded three hours early and final stowage delayed until 3:00 a.m. At that hour, the crew was preparing to board.[42]

Liftoff on the morning of 25 May 1973 was flawless. By midafternoon the crew had reached *Skylab* and found it very much as expected. "Solar wing two is gone completely off the bird," Conrad reported. "Solar wing one is . . . partially deployed. . . . There's a bulge of meteoroid shield underneath it in the middle, and it looks to be holding it down." Sunlight had blackened the gold foil on the workshop's exterior. More important, the scientific airlock was virtually free of debris. During the inspection, Weitz had trouble televising the damaged area from the spacecraft's cramped quarters, but Houston acknowledged "some pretty clear views." Conrad completed the flyaround, optimistic that the crew could free the array in standup EVA.[43]

The astronauts ate dinner before trying to extend the array. Weitz manipulated the tools while standing in the open hatch, as Kerwin held





The jammed solar array as seen from the Apollo spacecraft carrying the first crew to Skylab, *above.* SL2-4-272. *A closer view, left, of the fragment of the meteoroid shield that held the solar array against the side of the workshop. Segments of the solar panel can be seen partially deployed, lower left. The lighter gray area, lower right, is a reflection of the remnant of shield trapped beneath the array.* SL2-1-107.

his legs and Conrad maneuvered the spacecraft. When Apollo passed over the California tracking station 40 minutes later, the crew was having obvious difficulties. Absorbed in their problem, the astronauts were venting their frustration with four-letter words, while Houston repeatedly tried to remind them that communication had resumed. Conrad's report was gloomy; the metal strip wrapped across the array beam, though only a centimeter wide, was riveted in place by several bolts that had apparently fastened themselves to the array as the shield tore away. Weitz had pulled the panel with all his strength but to no avail. Conrad summed up the situation as the spacecraft headed into the earth's shadow: "We ain't going to do it with the tools we got."[44]

The crew then expected to end the work day by docking. When Conrad attempted it, however, the probe did not engage the drogue. He tried two backup procedures with no more success. Flight controllers proposed docking with the circuit breakers open, but this also failed. By 9:00 p.m., the crew was down to its last alternative, donning the pressurized suits to attempt another repair by EVA. While practicing that emergency procedure in Houston, Conrad had jokingly told Kerwin that if events ever reached that stage, they were coming home. Faced with a real problem, Conrad radioed Mission Control, "We might as well . . . try the EVA. Because if we ain't docked after that, I think you guys have run out of ideas."[45]

The procedure involved depressurizing the spacecraft, opening the forward tunnel hatch, and removing the probe's back plate to bypass some of the electrical connections. Then, centering the probe and drogue, the crew used the Apollo's thrusters to close on the docking adapter. When the two docking surfaces met, all 12 latches properly engaged. While the program managers held a midnight press briefing, the crew straightened up the Apollo cabin to close out a 22-hour day.[46]

ACCOMPLISHING THE REPAIR

Despite the first day's troubles, NASA officials remained optimistic about deploying the parasol. The crew entered the workshop in midafternoon on the 26th, having first activated the docking adapter and airlock. Weitz reported a dry heat, "like the desert." The crew proceeded deliberately, leaving the workshop on occasion for relief from the heat. The operation took about two hours. After connecting the parasol canister to the scientific airlock and opening the port, the astronauts threaded extension rods and gradually extended the parasol. When the folded arms finally swung outward, spreading the fabric, the crew was disappointed. Conrad reported that "it's not laid out the way it's supposed to be." He estimated that the wrinkled canopy covered only about two-thirds of its intended area. At Mission Control, however, the news of a clean deployment was greeted with cheers. Houston officials believed the wrinkles had set in during the cold of the lengthy deployment (the shade had been extended but unopened in the dark portion of the orbit) and they expected the material to stretch in the sunlight.[47]

The workshop cooled considerably in the next three days. The temperature on the external surface dropped 55° C overnight. Internal temperatures reacted more slowly, falling 11° C the first day. The outline of the parasol could be traced by running a hand along the workshop wall; the uneven coverage left hot spots, including an area near Joe Kerwin's sleeping compartment. By the 29th, engineers had concluded that the workshop would stabilize near 26° C, about 5° C above the desired level but still tolerable. Full-scale operations began that day with medical tests, solar observations, and preparations for the initial earth-resources pass. Power consumption ran very close to *Skylab*'s output of 4.5 kw, particularly when the crew operated the telescope mount, which drew 750 watts. At the evening news briefing, Flight Director Neil Hutchinson acknowledged that the power limitation was one of several problems complicating the early flight planning.[48]

The 30th brought yet another crisis. The earth-resource maneuver involved taking *Skylab*'s solar panels out of direct sunlight and relying on batteries for power. As the spacecraft passed through the earth's shadow, four batteries dropped off line. Despite repeated attempts, flight controllers could restore only three of them when the workshop returned to its solar inertial attitude. The loss, Skylab's second in a week, reduced power capacity by another 250 watts and raised serious doubts about the soundness of the electrical systems.* On the 31st, the Management Council moved the launch date for the second crew ahead two weeks because of the worsening conditions. The group discussed possibilities of freeing the solar array and set 4 June as the date for a decision.[49]

A team led by Rusty Schweickart had been studying the solar-array problem since the day after launch. Talks with the crew helped fill in some of the blurred televised pictures so that by the 29th, Huntsville had a reasonable facsimile of the jammed array. During the next four days, the group developed a difficult but feasible procedure. Exiting from the airlock port, two crewmen moved through the airlock trusses to the long antenna boom at the forward edge of the workshop. After attaching an eight-meter cable cutter to the debris, one astronaut used the pole as a handrail to reach the solar array. There he connected a beam-erection tether—a nylon rope with hooks at each end—between the solar wing and the airlock shroud; the tether would be used to break a frozen hydraulic damper on the array once the debris had been removed. The most difficult aspect of the operation was the lack of footholds which would allow the astronauts to work with both hands. By 2 June, however, Schweickart and Ed Gibson had demonstrated the procedure successfully in the water tank. What could be done there could usually be repeated in space.[50]

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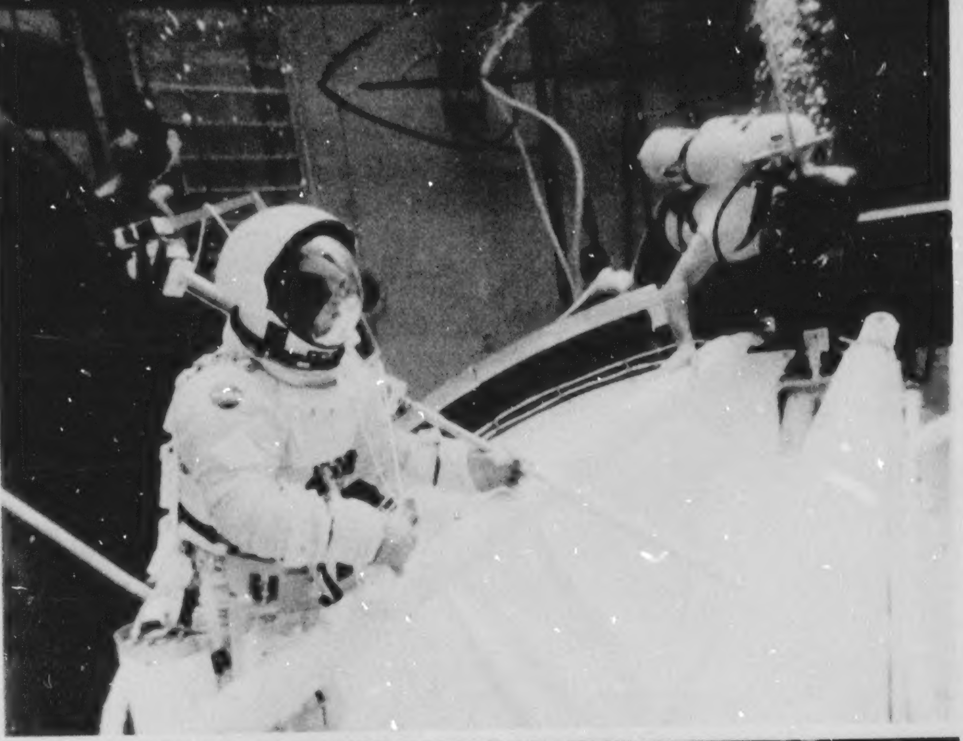
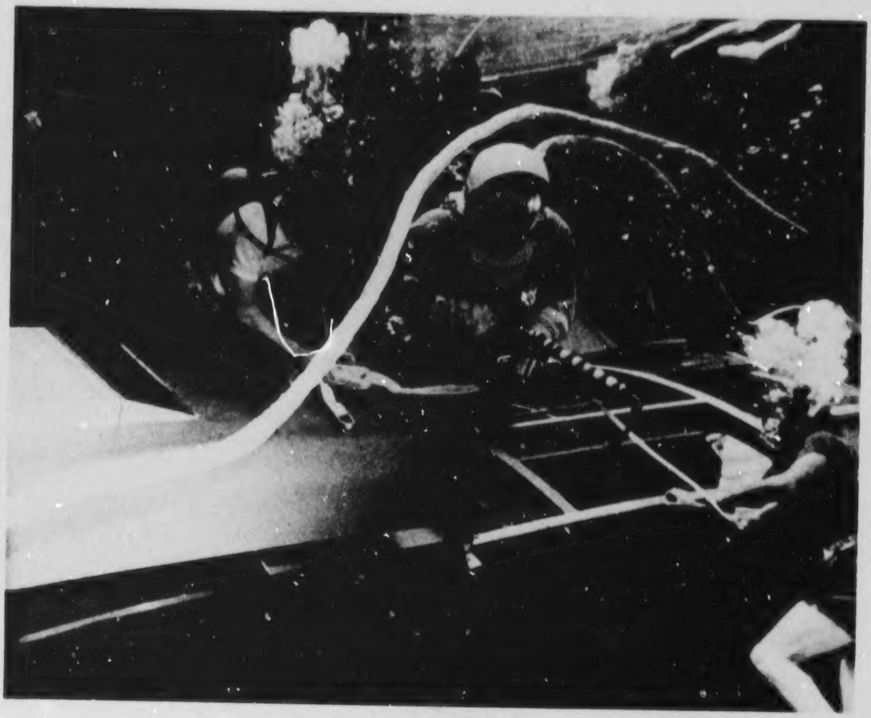
* The batteries were designed to drop out of the system when 80% of their charge was gone. Some of them, possibly weakened by the heat, stopped producing electricity when the charge dropped below 50%. The failure on the 30th was in a regulator. The battery could be recharged, but would not feed power into the larger electrical system.

In Huntsville on 4 June, the Management Council received a bleak picture of *Skylab*'s condition. If no more batteries failed, the first crew could probably complete the scheduled experiments. Without some additional power, the next two crews could not. Schweickart reviewed the procedure to free the solar array and showed films of his practice session in the tank. Some members expressed reservations. Attaching the cutter to debris eight meters away seemed a tricky maneuver at best, and there was no alternate way of securing the pole. Nor was it clear that the strap running over the solar array was the only thing preventing its release. Nonetheless, the group approved the attempt. The extravehicular activity was no more hazardous than other EVAs, and success promised large gains in power. Even failure might provide valuable information for a later attempt.[51]

That evening Schweickart gave the crew a brief description of the operation. After the crew was asleep, a list of tools, assembly instructions, and detailed steps followed over the teleprinter. The astronauts reviewed the procedure in their spare time and resolved a few questions during an hour-long session with Houston the following evening. On the 6th, the crew rehearsed the operation inside the workshop, communicating with Mission Control by television as well as radio. Kerwin donned his pressure suit for a more realistic simulation, and Conrad made several small changes in the beam-erection tether. Neither was particularly optimistic about their chances.[52]

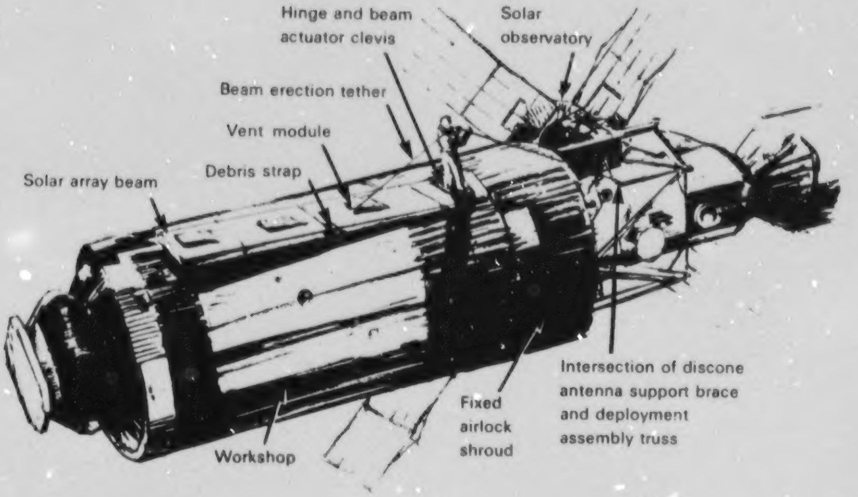
The crew opened the airlock hatch just before *Skylab* began a dark pass on the morning of 7 June. Conrad assembled the tools under the lights of the airlock shroud, and the two men moved to the antenna boom. When it was light enough, Kerwin tried to fasten the cutters. His initial attempts failed. In the Huntsville tank, Schweickart had placed his feet at the base of the antenna; on the flight model, cable connectors were in the way. As Kerwin recalled, "one hand was essentially useless—wrapped around the antenna—and with the other hand I couldn't control the pole. . . . Every time you would move it, your body would react and move the other way." On several occasions Kerwin got the jaws of the cutter close to the restraining strap, only to have the pole move as he brought his hand from the antenna to open the cutters. When Houston lost communications at 11:42 a.m., Kerwin had been hard at work over half an hour, his pulse reaching 150. Then Kerwin hit upon an idea that saved the day. He shortened the tether that ran from his suit to the antenna by doubling the line, thereby establishing a firm position against





Astronauts and engineers in Marshall's water tank, late May and early June 1973, experimenting with various cutting tools and techniques that might be useful in freeing the solar array. MSFC 040538, MSFC 040555, *and* 73-475.

Astronaut Russell Schweickart (at right) and Marshall engineers beneath a solar array beam, the piece of hardware that had to be freed to deploy the one solar wing that remained on the workshop. MSFC 040493.


Hinge and beam actuator clevis
Solar observatory
Beam erection tether
Vent module
Debris strap
Solar array beam
Intersection of discone antenna support brace and deployment assembly truss
Fixed airlock shroud
Workshop

Technique for freeing the jammed solar array. After cutting the debris strap, both astronauts would pull on the line to free the frozen actuator.

the edge of the workshop. Ten minutes later the crew notified Houston that the pole was fastened securely to the array.[53]

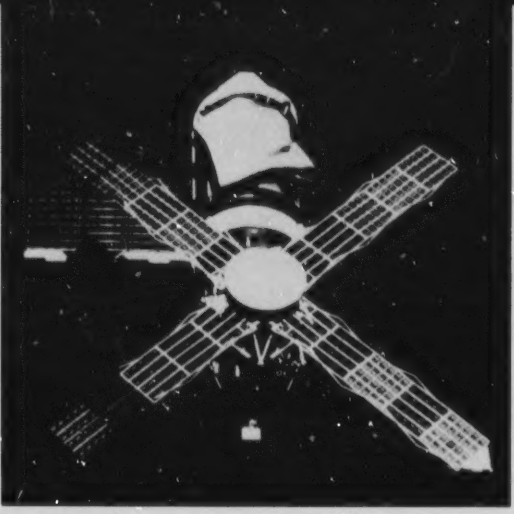
Although the worst was over, the crew had more problems. At the solar array, Conrad could attach only one of two hooks on the erection tether; the holes on the array were a bit smaller than those on the ground model. After struggling with the second hook for a time, he decided to make do with only one. Kerwin cut the restraining strap without much trouble, but releasing the frozen damper proved more difficult. The two men working together finally succeeded. Asked by Houston how the array had deployed, Conrad laughingly responded:

> I'm sorry you asked that question. I was facing away from it, heaving with all my might and Joe was also heaving with all his might when it let go and both of us took off. . . . By the time we got settled down and looked at it, those panels were out as far as they were going to go at the time.

By the next day they were fully extended and producing nearly 7 kw of power.[54]

Investigation Board

Congressional critics were quick to fault NASA for the accident. Senate space committee chairman Frank Moss called for NASA to in-



The repaired Skylab. *The sunshade, though not lined up with parade-ground precision, quickly made the workshop livable. The four solar arrays of the telescope mount are fully extended, as is the surviving array of the workshop. The photograph was taken by the departing first crew.* 73-H-580.

vestigate, which agency policy required in any event. On 22 May, Bruce Lundin, director of Lewis Research Center, was asked to head an inquiry. His committee first examined the flight data to establish the events surrounding the accident. Then, having settled on failure of the meteoroid shield as the primary cause of the accident, the board reviewed its development in great detail, concentrating on the management aspects of design, fabrication, and testing. The inquiry included visits to the three manned space centers and McDonnell Douglas's Huntington Beach plant before the report was completed in early July.[55]

The board examined 10 ways that the shield might have failed, but considered only 2 as likely. The first involved the space between the edge of the shield and the workshop wall. Although NASA had stipulated that the shield fit tightly against the tank, at launch the shield had gaps that exceeded design specifications by half a centimeter. Wind-tunnel tests confirmed that a buildup of pressure in these spaces could have led to the accident. Flight data, however, pointed toward the shield's auxiliary tunnel as the probable cause of the accident. The tunnel, used as a conduit for wires, was designed to vent pressure as the launch vehicle rose through the atmosphere. But the tunnel had not been constructed as designed, and pressure could build up.[56]

Lundin's committee theorized that the pressure may have become high enough to lift the shield into the airstream one minute after launch. As the shield ripped away, it wrapped around one solar array and broke the latches on the other. Forces of gravity and aerodynamic drag held the array close to the workshop for over eight minutes until the spent S-II stage separated from the workshop. When the stage's retrorockets fired, the exhaust tore the solar array from its hinge.[57]

Why had NASA and McDonnell Douglas failed to detect the deficiency in six years of development and testing? The board blamed the error in part on the presumption by Skylab engineers that the shield would fit tightly, as specified in design criteria. The actual shield proved to be a "large, flexible, limp system" that could not be rigged to design specifications. The committee criticized NASA's failure to treat the shield as a separate system with a project engineer responsible for all its details. There was no evidence that development had been compromised by a lack of time, money, or expertise. Instead, the committee attributed "the design deficiencies . . . and the failure to communicate within the project . . . to an absence of sound engineering judgment and alert engineering leadership concerning this particular system over a considerable period of time."[58]

Among the board's specific recommendations, three had broad significance for NASA management. One called for the appointment of a project engineer on complex items that involved more than one engineering discipline. The second warned against undue emphasis on documentation and formal details: "Positive steps must always be taken to assure that engineers become familiar with actual hardware, develop an intuitive understanding of computer-developed results, and make productive use of flight data in this learning process." Finally, the board encouraged the assignment of an experienced chief engineer to major projects such as the workshop or airlock. Freed from administrative and managerial duties, he would "spend most of his time in the subtle integration of all elements of the system under his purview."[59]

15

The First Mission

The first crew crammed enough drama into two weeks to last the entire program. Aside from the repair, there were controversies regarding communications and the crew's health. NASA's public affairs chief clashed with the Office of Manned Space Flight over private communications—whether the American press should be excluded from air-to-ground discussions about operational and medical problems. The Office of Public Affairs feared that private conversations would harm relations with the press; OMSF believed that forbidding private communications could endanger the mission. While this matter was debated, crewmen struggled with the ergometer, *Skylab*'s principal means of exercise. They devised a satisfactory means of riding the machine, but not before the strenuous activity caused a misunderstanding about their health. In the last two weeks of operations, with the additional power from the released solar array, the astronauts completed most of their assigned tasks.

PRIVATE COMMUNICATIONS

Since its earliest days, NASA had prided itself on the openness of its programs—in sharp contrast to the secrecy maintained by the Soviet Union. The agency kept newsmen abreast of missions with transcripts of air-to-ground transmissions and frequent briefings. The policy worked well until the late 1960s, when the press began complaining of a credibility gap. Several newspapers viewed a private conversation from *Apollo 9* as a move away from NASA's open policy; the *Washington Post* noted that space officials were debating "how much to tell the public about some of the more intimate details of space flight," and the *Houston Post* argued that the public had a right to medical information about the astronauts. In March 1969 Administrator Thomas Paine reiterated his support for an open program with private communications limited to special medical situations or operational emergencies. Any private conversation would be summarized for the press. NASA followed an open policy for the remainder of Apollo, although Houston officials chafed at the restriction, preferring candid discussions with the astronauts over a private line.[1]

For Skylab, JSC proposed to modify agency practice, justifying the changes on the length and the peculiar medical requirements of the program. The proposal established private medical conversations on a daily basis. The flight surgeon would inform the press of any significant medical news, but the tapes would be neither released nor transcribed for the news media. Private programmatic communications were permitted "when a real operational need existed." A public affairs officer would monitor any private communication of this nature and summarize substantive matters for the press. There were also provisions for weekly unmonitored calls between the astronauts and their families.[2]

OMSF endorsed the Houston plan, noting that doctor-patient relations were considered privileged since most people were unwilling to discuss their physical conditions openly, and the astronauts were "no exception to this generally accepted and widely known situation." Although the press received medical information on public figures, the bulletins contained only those details considered appropriate for release; specifics were often withheld. Private communications would help NASA doctors ascertain important preliminary symptoms, complaints that nearly everyone—including astronauts—would ignore under ordinary circumstances. OMSF expressed dissatisfaction with the practice of paraphrasing private medical conversations, citing the *Apollo 15* experience when NASA managers had wanted information on James Irwin's irregular heartbeat,* but feared that adverse publicity would threaten the remaining missions. At certain times, private communication would benefit the program without depriving the public of its right to know.[3]

John Donnelly, assistant administrator for public affairs, moved quickly to head off any change in policy, informing Administrator James Fletcher in January 1973 that he and OMSF could not agree. Private conversations with families posed no problems, but Donnelly strongly opposed routine medical conferences on a private loop. "It seems to me the condition of the men in the machines is as much, if not more, of a news element than the condition of the machines—particularly on a mission like Skylab." Donnelly doubted that private medical communications would encourage astronauts to report "freely and honestly their physical condition." Pilots were in general reluctant to admit problems that might shorten a mission or make them more dependent on the ground. He personally doubted that a private line would improve communications and feared the point would cloud the real issue: "Should the agency abandon a successful and respected policy which has won world-wide acclaim . . . ?"[4]

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* This occurred in lunar orbit, following three tiring days on the moon. NASA doctors later attributed the excessive fatigue to a low level of potassium.

In March 1973 Fletcher adopted a compromise that allowed routine medical discussions over a private line. Conversations would not be paraphrased, but the flight surgeon would provide newsmen with summary bulletins. The administrator also approved private operational communications "in matters of extreme emergency." The calls could be initiated by flight controllers or the crew and would be paraphrased for the press by the public affairs office.[5]

The new policy was tested less than a week after launch of the first crew. Pete Conrad shared the dislike of many Houston officials for the open policy. While acknowledging the public's right to know about NASA decisions, he believed that discussions leading to such decisions should be private. Late on 28 May, Conrad asked for a private conversation the following morning, saying, "It's not [garbled] any emergency right now." Several NASA officials were roused from bed to discuss the commander's request. Despite the protests of the public affairs office, Schneider approved a private loop. Donnelly wanted the crew reminded that a private communication required an emergency, but Deputy Administrator George Low turned down the suggestion.[6]

The private communication on the 29th widened the rift between OMSF and the public affairs office. Conrad began by apologizing for the difficulty he had experienced riding the bicycle ergometer (see pp. 284–86). From there, the conversation moved to other problems including the solar array, docking probe, and workshop temperatures. Conrad expressed surprise that the mission was going so well and reported the crew "in good shape." When newsmen received a summary an hour later, they questioned whether an emergency had really existed. Donnelly publicly stated that the situation had not justified a private communication and that ground personnel had erred in arranging one. Privately, he sought to release the tape of the conversation and have Conrad formally reprimanded. Although neither action was carried out, Dale Myers agreed to have the capsule communicator in Mission Control ask the crew if an emergency existed before arranging another private communication.[7]

A second controversy that day concerned the information recorded on board and relayed to the ground at intervals. This material was called "channel B dump data" to distinguish it from live air-to-ground conversations over the primary channel. In February, Conrad had mistakenly told a press conference that newsmen would receive transcriptions, although the agency actually planned to treat the recordings as confidential. The matter was forgotten until the 29th when the availability of the tapes became an issue. At Donnelly's insistence, Myers initially agreed to release all channel B data, but then excluded information on medical experiments: Houston's doctors did not want sensitive medical data released to the public lest laymen draw erroneous conclusions. Donnelly appealed to Low, arguing for the release of all channel B material to allay a "climate of mistrust." He cited a possible challenge under the Freedom of Information Act and concluded, "It is a bad idea to censor this type of material because it calls into question the completeness of everything else we put out." Low honored the doctors' request, however, pending a full discussion with Fletcher.[8]

On the 31st, the administrator rescinded the requirement that Mission Control question the crew about the seriousness of an operational problem, fearing that such questioning might inhibit the crew from raising matters of concern. In a press release Fletcher said, "We do not want to risk the safety of the flight by having the astronauts infer, from our questions, that they should not use the private communications loop when a real need might exist." The wording reflected George Low's view that "extreme operational emergencies" included any matter of "real concern" to the crew that could not be resolved over an open line. Fletcher also approved Myers's refusal to release medical data on the channel B tapes; the practice was in keeping with NASA tradition and the information had been promised to the medical investigators on a proprietary basis.[9]

Fletcher's press release clarified NASA policy, but did not settle the issue of private communications. Donnelly remained suspicious of his NASA associates and fearful of a credibility gap. After the launch of the second crew, he warned Fletcher that reporters for *Time,* the *New York Times,* and the *Chicago Tribune* were unhappy about deviations from the traditional open policy. These representatives were particularly concerned that the trend toward routine private conversations would weaken their negotiating position with the Soviet Union regarding communications for the Apollo-Soyuz flight. Donnelly's aggressive defense of the newsmen's interest may have affected his own credibility within NASA, because the press did not appear that concerned—at least not in print. Absorbed with Watergate, newspapers gave *Skylab* relatively little attention, and most coverage focused on the crews' success; little was written about private communications.[10]

With one exception, *Skylab* crews avoided private operational conversations after 29 May, perhaps from fear of further controversy. Conrad, for one, believed the lack of a private line inhibited communications. After the mission he complained "that all too often he was left in the dark" concerning Houston's plans. He cited, as an example, learning from his wife, during a birthday greeting, about EVA plans to free the solar array. He acknowledged that more information could pass over open lines, but thought that Houston officials would be more candid over a private channel. The lack of a private operational channel had little apparent adverse affect on the first two missions; on the last flight, however, the open policy would contribute to the poor communications between Houston and the crew. In the issue of private communications, the agency's political interest ran counter to its operational needs, and no satisfactory compromise was achieved.[11]

Physical Fitness in Space

NASA's astronauts and doctors had disagreed about medical experiments since Gemini days. Astronauts felt they were being treated like guinea pigs in what were often viewed as unnecessary experiments. Mike Collins called the inflight sleep analysis experiment on *Gemini 7* "a classic case of the tail wagging the dog, with decisions to be made by the wrong people (the medics) in the wrong place (the ground) with the wrong information (brain waves)." The medical directorate, on the other hand, viewed its experiments as a key element of manned spaceflight and insisted on rigid controls. Dr. Charles Berry acknowledged that most agency managers, as well as astronauts, considered his staff "over cautious"; but he believed the caution was justified. NASA was under substantial pressure from critics of manned spaceflight, and it was important to make sound judgments about the astronauts' adjustment to space.[12]

Physical exercise was one of the activities disputed by the two groups. Doctors wanted to control exercise before and during a mission

Kerwin in the lower-body negative-pressure experiment M092. Weitz is helping him attach sensors. The purpose of the experiment was to provide information concerning cardiovascular adaptation in space and impairment of physical capacity upon return to earth. SL2-2-180.

because of its medical implications; ideally they would measure all physical activity. Astronauts objected to rigid controls because of personal inconvenience, as well as a belief that they could best judge their need for exercise. The compromise worked out, for Skylab made no attempt to regulate all exercise; the medical office settled for periodic measurements of physical condition. Daily exercise was left to the individual astronauts, with the understanding that crew members would report how long and hard they had worked. The ergometer, the principal exercise machine, provided a means of gauging the workload.[13]

The first crew was allowed, by the flight plan, 30 minutes a day for exercise on either the ergometer or an isometric device. Twice a week each crewman tested his physiological response to exercise by performing the metabolic experiment, M171. More specifically, M171 measured the changes in metabolic response to work, charting blood pressure and heart rate as well as oxygen consumption.* There were five periods to the 25-minute test: a rest phase to establish the metabolic rate; three periods of exercise at 25%, 50%, and 75% of the crewman's maximum capacity for work (determined in preflight tests); and a recovery phase. A secondary purpose of M171 was to evaluate the ergometer as an exerciser for long-duration flights. During the lunar missions, the crew's ability to exercise had been limited by the size of the Apollo spacecraft, and most astronauts had shown a decline in physical conditioning. The loss was temporary (within 36 hours they normally returned to preflight levels of exercise), but it indicated a potential danger for long-term flight.[14]

Problems with the ergometer surfaced during Weitz's first run of the metabolic experiment on 28 May. Because of the heat in the workshop, Kerwin had recommended shortening the schedule for M171. Houston encouraged the crew to attempt the entire exercise, since deviation would affect experiment controls. Midway through the third level of the exercise, however, Weitz called it quits. The waist and shoulder harness—intended to secure the astronaut to the bicycle—was restricting his movement. Weitz found that he was doing too much of the work with his hands, not enough with his big leg muscles.† During the private communication on the 29th, Conrad reported that the ergometer could not be ridden in space as it had been on earth and questioned whether the crew could finish the full regimen. A few hours later, Kerwin too failed to complete the exercise. Conrad persisted to the end but compared the third level to "20 minutes of a full workload." He told Mission Control: "I was really running out of gas. And yet, I was using muscles that I don't normally use on the ground." The crew recommended lowering the workload (amount of resistance in the ergometer pedals) by 10-20% to compensate for the difficulty of riding in space.[15]

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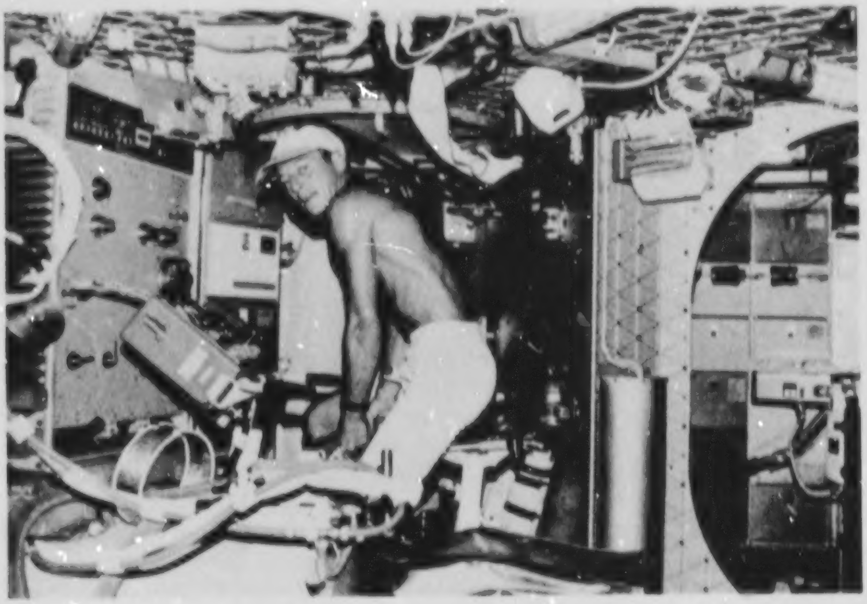
* Many readers will recognize M171 as an aerobic exercise. Aerobic, "living in air," in the last decade has taken on the additional meaning of physical activity that increases heart and respiratory activity for a sustained period of time.

† Caldwell Johnson had argued that the ergometer would not work in space and had provided an alternate design. Why it was rejected is not completely clear.



Conrad riding the ergometer as the experiment's principal investigator had envisaged, above, SL2-8-714, *and in his own zero-g adaptation, right.* SL2-9-742.

The initial problems on the bicycle were aggravated by a tight schedule that reduced the crew's physical exercise. On 31 May Kerwin complained that Houston's flight plan was effectively eliminating the period of physical activity: "It's been scheduled strictly on paper, as far as we're concerned, because the other scheduled tasks have taken so much time that they have completely absorbed and wiped out PT [physical training]." Too often exercise was scheduled just before or after a major activity having a fixed time requirement. Kerwin considered this a serious mistake and hoped that Mission Control would give the exercise period "priority over most other objectives."[16]

During the second week, the crew experimented with different positions on the ergometer, eventually discarding the harness altogether. The astronauts found that they could stabilize themselves by locking their triangular cleats into the pedals and placing their hands against the ceiling or on the handlebars. According to Weitz, it was "a revelation . . . it's so much easier than strapping yourself down." Conrad displayed a knack for "arm ergometry," pedaling with his hands while his feet pressed against the ceiling. After discarding the harness, and after the workshop had cooled down, the crew returned to preflight levels of exercise. At a press conference on 6 June, Edward Michel, principal investigator for M171, acknowledged that elimination of the harness affected the controls for his experiment just as the first week's excessive heat would have to be considered in assessing the initial runs. He seemed relieved, however, that the crew had found a way to ride the ergometer.[17]

On 4 June the crew began plans to free the solar array, confident that they had resolved their difficulties on the ergometer. Houston's doctors were disturbed, however, by the initial results from the M171 experiment. Pulse rates had run abnormally high, and Conrad showed a series of heart palpitations.* The medical office had said nothing about the matter to the press or the crew; in fact, the doctors had not known the details for several days because of delays in the flow of data. They attributed the high rates to the heat and harness, but some thought they might be seeing early effects of weightlessness. The doctors were particularly anxious to retest Conrad before he attempted extravehicular activity. That evening Charles Ross, the crew's physician, told Conrad about the problem and said that Houston was making special plans for his M171 run the next day, scheduling the experiment over North American tracking stations so that the medical office could receive the data quickly. The doctors recommended that Conrad reduce his maximum workload. If he showed further palpitations, the doctors wanted him to avoid strenuous exercise—including the extravehicular activity.[18]

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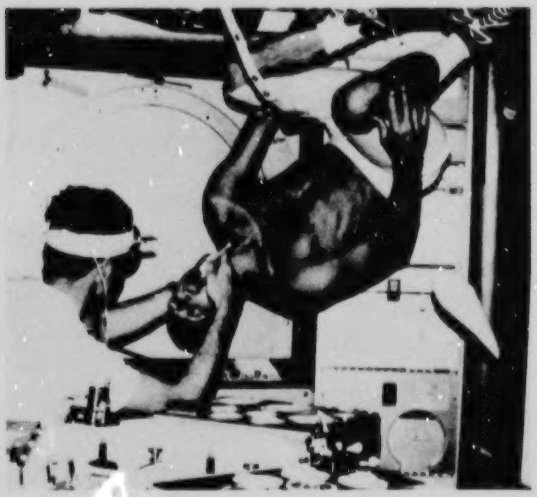
* In a press conference on 5 June, Dr. Royce Hawkins described Conrad's condition as a premature ventricular contraction, but indicated that the condition was not uncommon.



Dr. Kerwin giving physical examination to the commander of the first crew. SL2-2-157.

The crew was taken aback, believing that the doctors had overreacted to outdated information. Conrad was particularly upset by Houston's failure to ask Dr. Kerwin or himself for a personal evaluation. Before his M171 run on the 5th, Conrad requested a private communication to clarify the medical situation. Over the private line, the crew told Skylab officials that they were in excellent condition and wanted to exercise as much as possible. Kraft expressed regret at the apparent misunderstanding and assured the crew that there was no doubt about their good health. In fact the medical office had altered its plan since the previous evening, but had not told the crew. The new instructions left the M171 workload to the crew's discretion.[19]

The matter was closed that afternoon when Conrad ran the full M171 protocol without difficulty. There were no attempts thereafter to play down the importance of exercise. Conrad would later describe the incident as "a very key thing in the whole flight." At the end of the mission he was in better condition than his crewmates, presumably because of his higher level of exercise. At the first crew's urging, Houston increased physical activity on later missions, with beneficial results.[20]

FLIGHT PLANNING: THE ASTRONAUTS' VIEW

The astronauts found the first week's schedule too demanding. On some tasks there was little difference between operating the trainer and the flight model; but other activities, such as handling small items or locating equipment in stowage, took much longer in zero gravity than expected. Although additional time had been allowed for them to become acclimated, the astronauts ran behind schedule (as would the later crews, at the start). The problem was compounded on the first mission by inexperience at Mission Control. Skylab operations represented a considerable change from Apollo, and coordination occasionally faltered during the first week.[21]

The men spent the first three days activating the hot workshop. They adjusted to space quite well, showing no sign of motion sickness, but found the pace fatiguing. When operations began on the 29th, the astronauts worked past dinner to complete their assignments. After a second hectic day, Conrad concluded that the schedule was unrealistic: "We were trying to do it all . . . and were getting inefficient by rushing." He informed Mission Control that the crew was "running all over the spacecraft," and that there were "enough guys down there to think out the flight plan a little better than you're doing." On the 31st Conrad offered a number of planning suggestions: allotting more time for housekeeping and individual experiments, scheduling one crewman to perform an entire procedure, and minimizing the loss of time between experiments.[22]

A holiday on 1 June gave the crew a chance to relax and catch up on housekeeping chores. During a 15-minute telecast, the astronauts performed acrobatic feats and their own "Skylab 500." Conrad had wagered some Houston friends before launch that centrifugal force would allow him to overcome weightlessness and walk erect on the storage lockers that circled the upper deck of the workshop. Starting on their hands and knees in a slow crawl, they built up speed and moved to a crouch, then finally walked rapidly on the lockers. The television pictures provided the proof.[23]

Much of the second week was spent on freeing the solar wing. The full schedule of experiments was resumed on the 9th, following a day of housekeeping and relaxation. After the excitement of the first two weeks, normal operations seemed humdrum; Kerwin recalled one evening when "it seemed like it had been day 18 for a week." As the astronauts adjusted to their surroundings, they frequently found themselves ahead of schedule. They decided not to ask for more work, however; preparations for the return to earth would take up much of the last week, and they did not want to set unrealistic standards for the next crew.[24]

FLIGHT PLANNING: THE INVESTIGATORS' VIEW

Skylab's first three weeks in space was a trying time for the principal investigators. For 10 days they faced the possible loss of years of work. After the crew's launch, the shortage of electricity caused further anxiety, and many scientists viewed each day as the last chance to gather data. "The risk of the mission being cut short," John Disher recalled, "was a big factor in the almost frantic approach of some . . . experimenters." If anything, the problem was acerbated by the apparent quality of the science. The investigators were pleased with the initial data, but as Robert Parker, program scientist, put it, "They felt starved for it." Few

Kerwin strapped into his sleep restraint and wearing the instrumented cap for the sleep-monitoring experiment M133, which evaluated the quantity and quality of sleep during prolonged spaceflight. SL2-3-205.

scientists thought they were getting their rightful share of the flight plan, and Parker (who had assumed responsibility for scheduling experiments just a few months earlier) did not enjoy their trust. Consequently, "most of them thought their experiment was the only one that had been reduced in scope." Karl Henize, a scientist-astronaut and investigator for an experiment in stellar astronomy, recalled a feeling of frustration bordering on paranoia: "You never quite knew what the other man's problems were, and you'd put in your requirements and you'd get them back all mangled. . . . everybody was mad at each other."[25]

The return of full electrical power did little to ease scheduling pressure. Investigators were anxious to make up the time lost in deploying the parasol and solar array—about 15% of the time allotted for science. At a news briefing on 8 June, Parker likened his problem to cramming a size 10 foot into a size 8 shoe: something had to give. Medical experiments retained their priority; during the last two weeks the crew actually increased the frequency of cardiovascular and metabolic tests. The earth-resource experiments, hard hit by the initial power shortage, were given a high priority, as were the solar observations. Conversely, the corollary experiments took a lower priority. Parker tried, however, to give everyone some time in the flight plan. By mission's end on 22 June, the crew had reduced the shortfall of experiment hours, meeting nearly 100% of the medical requirements and 80% of the solar observations. Earth resources remained the hardest hit of the major experiments; because of the shortened runs during the first half of the mission, the crew conducted only 60% of the work programmed for that area.*[26]

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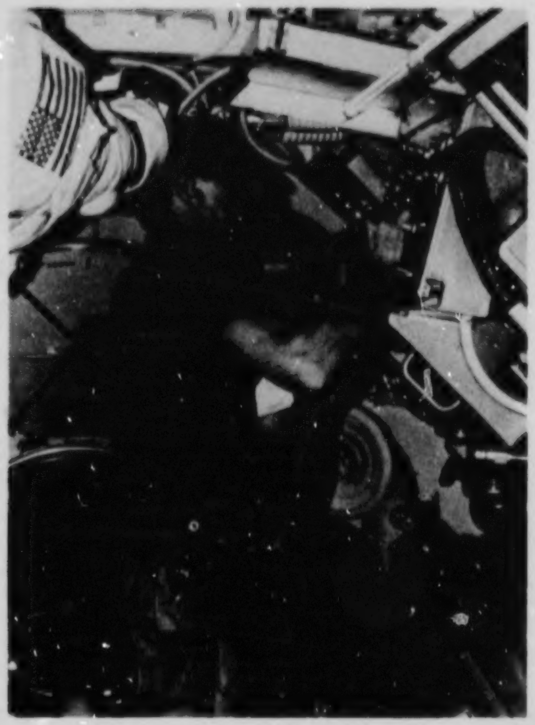
* Understandably, NASA officials stressed the amount of work accomplished rather than the shortfall. The first crew took 29 000 pictures of the sun and 14 kilometers of magnetic tape for earth resources. See chap. 18 for a detailed treatment of results.



Conrad and Weitz working with the materials-processing facility M512. SL2-9-738.

While most scientists expressed satisfaction with the results of the first mission, some investigators, according to Parker, "felt they had really gotten gypped." The general mood was "that they had put an awful lot of their time and NASA's money into getting very little data, and they'd better jolly well get more time . . . in the next mission." During the next two missions, Parker sought to placate his colleagues with periodic planning sessions. The meetings proved helpful, allowing the investigators to gain an appreciation for each other's problems. Even more helpful in alleviating discontent, however, was the steady stream of data from *Skylab.*[27]

THE LONG-AWAITED SOLAR FLARE

With its various switches, monitors, and checklists, the console for the solar telescopes was a complicated station. After working with it some time, one astronaut concluded, "there's no way to go very long . . . without making a mistake, you just hope that you don't make any that are too large." Kerwin acknowledged a lot of mistakes on the first mission, attributing most of them to frequent interruptions. "We never got to buckle down into the ATM routine up there, at least not for more than a few days at a time."[28]

One of the biggest problems with the ATM console was its flare detection system. Designed to alert the crew if a solar flare developed while no one was at the console, it frequently went off as the workshop passed over the eastern part of South America, where the earth's radiation belt dips much lower. The magnetic field triggered the flare alarm whenever the crew left the system running. Kerwin later recalled his frustrations with the detector: "Every time I left the alarm on, it wasn't 5 minutes until the alarm sounded. Then somebody had to break loose from what he was doing, go up to the ATM console, and turn it off. . . . I never realized that [the South Atlantic anomaly] was so ubiquitous." Allowing for exaggeration, the false alarms were a frequent disturbance which the crewmen put up with to catch a flare. Kerwin's eagerness, in fact, proved an early embarrassment. On 30 May, reacting quickly to an alarm, he forgot that he was over the South Atlantic and started the procedure for recording a flare; fortunately he realized what had happened before he wasted much film. While Kerwin gracefully accepted the teasing about his mistake, the incident did not increase his enthusiasm for the alarm system. After the mission, he evaluated it as "absolutely worthless."[29]

For three weeks, the first crew's hopes for a flare went unfulfilled; then on 15 June persistence was rewarded. The astronauts had agreed to give up their free day to make up lost time on the experiments, but the outlook for solar activity was not promising. Houston reported a few subnormal flares and a possibility of more action, to which Kerwin responded: "We'd like some supernormal flares, please." Five hours later the mission's first good-sized flare was spotted. Kerwin told Houston: "I'd like . . . you to be the first to know that the pilot [Paul Weitz] is the proud father of a genuine flare." The solar scientists were extremely pleased that Weitz had tracked the flare through two minutes of its rising portion and the subsequent fall, a task that involved monitoring several displays to confirm the solar activity, initiating several flare programs, and then pinpointing the flare with the solar telescopes—all within a matter of seconds.[30]

Any disappointment that the crew may have felt about its ATM work was not shared by the principal investigators. During the course of Skylab's development, solar scientists had been, at times, among the program's most vocal critics. Many noted astronomers questioned the wisdom—at least the cost—of manning solar telescopes in space (p. 81). This attitude changed dramatically as the results began arriving.[31]

CRITIQUE OF THE FIRST MISSION

The crew gave *Skylab* high marks in the postflight debriefings. With a few exceptions, experiment hardware worked satisfactorily. The multispectral scanner (one of the earth-resource instruments) caused Weitz much unhappiness. "Adjusting the focus completely messed up the alignment. More than once we lost the alignment completely. It just dropped off the bottom of the scale." As a result, 3 of the 12 passes with the multispectral scanner were of marginal quality. All three crewmen complained about calibrating the body-mass measuring device. Each astronaut's weight was determined daily by measuring the oscillatory frequency of a spring-mounted chair. Three times during the mission the device was calibrated, using objects of known mass; the problem was getting the items—in particular, several heavy batteries—to stay in place during the calibration. For the most part, however, hardware performance surpassed the crew's expectations.[32]

The crew gave the support team many compliments. Weitz "could not say enough about the high-fidelity trainers," and Kerwin noted that training personnel had even "put in the failures and the sticky parts." Most checklists worked well, except for inflight changes; there was no easy way to catalog teleprinter messages for later reference. Conrad recommended that the next crew take notebooks and keep teleprinter messages in a permanent file. Channel B communications also needed improvement; when the astronauts replied to queries, their answers—sent down over the secondary channel—sometimes disappeared for days.[33]

If the astronauts were satisfied with *Skylab* as a home, they could not recommend it as a restaurant. Food seemed to lose its flavor; bread that had tasted "very good" in Houston was "very much different and . . . worse tasting" in space. Generally, the astronauts' preferences remained the same. Weitz's comment was typical: "The foods I liked I continued to like. The foods I didn't like, my dislike for them increased." One noticeable difference was the desire for spicy foods, which the astronauts attributed to their loss of taste and smell. (The crewmen's senses were

Alan L. Bean, commander of the second crew, on the body-mass measuring equipment of experiment M172. 73-H-974.

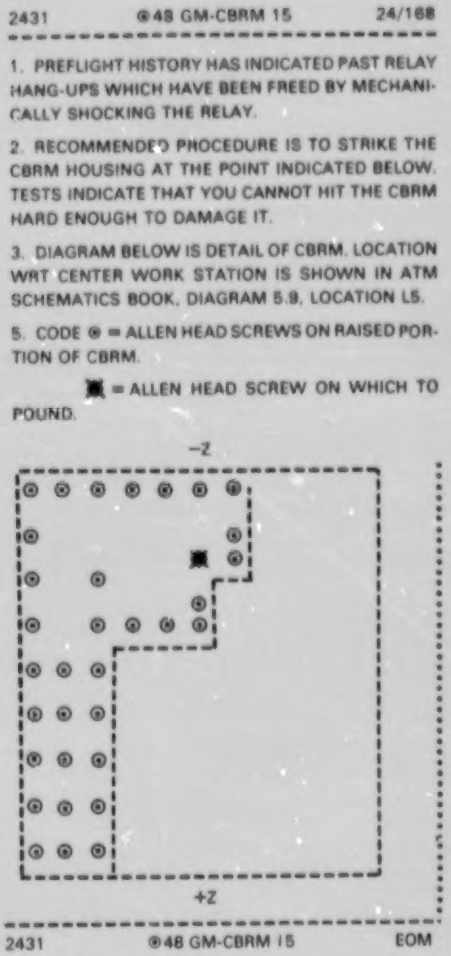
Conrad turns barber, Weitz holds a vacuum hose. Note how the food trays were attached to the sides of the small galley table. The much-debated wardroom window is in the background. SL2-9-755.

probably dulled by head congestion, a result of blood pooling in the upper regions of the body.) German potato salad, long on vinegar and onions, proved so popular that the crew used up all four cans on board. As for categories of food, the frozen foods were rated most acceptable and the reconstituted items the least satisfactory. Conrad recommended that the next crew take some spicier foods along and allow more time to reconstitute the dehydrated items. "I found that if I reconstituted the peas, the beans, and the asparagus early, and then reheated them, I still didn't like them, but they were a lot easier to choke down than when I added the hot water, shook up the bag and then tried to get them down."[34]

Matters were made worse by the astronauts' rigid diet; with fixed menus, they knew when to expect the undesirable foods. The diets provided some variety, but not enough. Kerwin recalled that "foods that we did pick were not palatable to us when taken repeatedly, partly because we just didn't eat that kind of food that often." He recommended that future programs use a plan originally considered for Skylab, in which categories of food were defined and items within a category were interchangeable.[35]

Despite the shortcomings of the cuisine, the crew obviously enjoyed the flight. Where else could one perform such acrobatics or enjoy such a

The medical experiments did not end with return to earth. Here Kerwin undergoes one more check aboard U.S.S. Ticonderoga, *22 June 1973.* 73-H-544.



2431 ⊙48 GM-CBRM 15 24/168

1. PREFLIGHT HISTORY HAS INDICATED PAST RELAY HANG-UPS WHICH HAVE BEEN FREED BY MECHANICALLY SHOCKING THE RELAY.

2. RECOMMENDED PROCEDURE IS TO STRIKE THE CBRM HOUSING AT THE POINT INDICATED BELOW. TESTS INDICATE THAT YOU CANNOT HIT THE CBRM HARD ENOUGH TO DAMAGE IT.

3. DIAGRAM BELOW IS DETAIL OF CBRM. LOCATION WRT CENTER WORK STATION IS SHOWN IN ATM SCHEMATICS BOOK, DIAGRAM 5.9, LOCATION L5.

5. CODE ⊙ = ALLEN HEAD SCREWS ON RAISED PORTION OF CBRM.

■ = ALLEN HEAD SCREW ON WHICH TO POUND.

2431 ⊙48 GM-CBRM 15 EOM

Teleprinter message sent to first Skylab *crew, giving instructions for repair of charger-battery-regulator module during extravehicular activity.*

marvelous view? Moreover, the mission had been a huge success. Despite personal and mechanical problems, ground and flight crews had persevered. The last extravehicular activity provided a fitting climax. The primary goal had been to replace ATM film; as a secondary objective Houston wanted to try to reactivate one of the dead power modules on the electrical system (p. 258). After reviewing test results, Huntsville engineers had concluded that a relay was stuck and that a blow to the battery housing would free it. Following instructions sent up by teleprinter, Conrad jarred the housing smartly with a hammer, and within minutes electricity was flowing again.[36]

16

The Second Mission

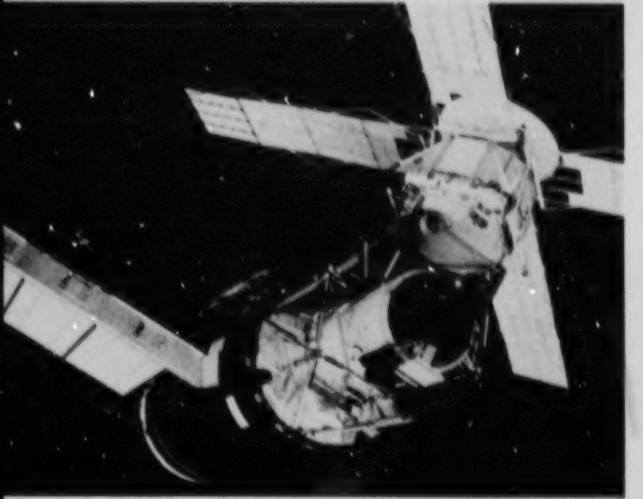
The succession of battery and gyroscope failures early in the mission had raised serious doubts whether *Skylab* could survive two months without a crew. After determining that the medical office and the launch center could meet an earlier date, launch of the second crew was advanced three weeks.[1]

The launch on 28 July 1973 was without incident, but the crew encountered serious problems in space. All three men suffered from motion sickness to the extent that they fell significantly behind schedule. Several mechanical difficulties also threatened to cut the mission short, but all were resolved. In the end, the second crew, determined to make up for a slow start, became overachievers.

Motion Sickness

While adjusting to weightlessness, a number of astronauts had been afflicted by motion sickness. Although the 19 Americans who had flown in Mercury and Gemini had been immune to the poorly understood malady, almost half the Soviet cosmonauts, flying in the slightly larger Vostok and Voskhod spacecraft, had suffered from it. With the start of Apollo, the Americans lost their immunity; 9 of 29 astronauts had motion sickness in that program, with nausea and vomiting persisting in some cases for several days. Because the problem was occurring in the larger vehicles, some doctors believed the increased freedom of movement—particularly head movement—brought on the malady. It had been a pleasant surprise, therefore, when the first *Skylab* crew remained free from motion sickness. Conrad cautioned against undue optimism during a postflight press conference, predicting that future astronauts could "experience some form of . . . motion disturbance that may . . . take more than a few seconds to get used to."[2]

His warning was borne out less than an hour after launch of the second crew, when pilot Jack Lousma complained of nausea. A capsule



The second crew photographed Skylab's *docking port, 28 July 1973.* SL3-114-1660.

of scopolamine–dextroamphetamine, a medication that blocks the nerve endings to the stomach, provided some relief, and he managed to eat lunch. The illness returned in greater intensity that afternoon as the crew began activating the workshop. By 6:00 p.m. all three men were experiencing motion sickness, Lousma the worst.[3]

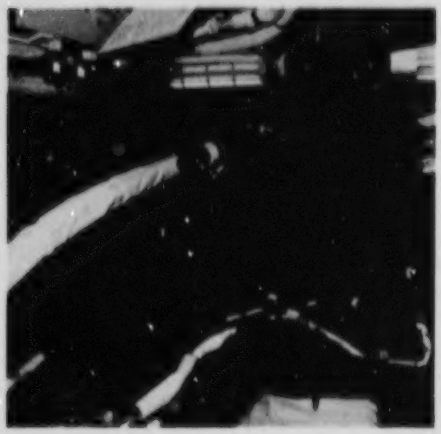
They showed no improvement the next morning; breakfast went half-eaten. At 8:30 a.m. Bean reported, "Although we're moving around getting things done, we're not doing them as rapidly as we'd like to." At lunchtime the crew still had no appetite, and the commander requested a break so that they could "get in the bunk and just stay still for awhile." He also asked Houston to consider giving them the next day off. Mission Control agreed to the midafternoon rest, but the crew had to spend most of the time trying to resolve an electrical problem in the spacecraft. That evening the astronauts had fallen nearly a full day behind schedule; NASA officials postponed a planned EVA for at least one day.[4]

In Houston, the crew's condition touched off a dispute as to the best cure for the illness. Dr. Ashton Graybiel, principal investigator for experiment M131, had found that subjects adjusted to a slowly rotating room more quickly when they made rapid head movements, as compared to remaining still. He wanted the crew to conduct a series of head movements three times a day—30 to 40 per minute for 10 minutes at a time—and warned that the astronauts would not get well by resting. Graybiel had Dr. Berry's support, but a number of Houston officials (most of them from outside the medical office) were openly skeptical. After the second day, Houston asked the crew to continue activation tasks at their own pace and also try the head movements. The astronauts undertook the exercises reluctantly, since movement increased their nausea; on the 30th Garriott worked through the exercises twice and Bean once. Lousma avoided the exercises altogether.[5]

Although the worst of the illness was over by the third day, activation problems kept the crew behind schedule. Bean blamed much of their trouble on unscheduled tasks. "We seem to end up with about as many new chores . . . as old. . . . We're having difficulty progressing because we're doing other work." That afternoon the astronauts spent five man-hours troubleshooting the workshop's dehumidifier and another hour repairing the urine separator. Time was also lost searching for personal items. As Bean remarked, "Everytime you go to do something like get your kit out and shave, you find there are no shaver heads there, and you have to go hunt . . . somewhere." After the flight he would attribute much of the sickness to the first week's hectic pace. "While we were doing activation . . . the whole thing was hustle all the time. . . . Half of the problem we had [in] adapting to motion sickness was caused by the fact we were not eating on time, we were not getting to bed on time, and we were not exercising." For future flights, Bean recommended that meals and rest be given priority over activation requirements, taking a day or two longer if necessary.[6]

The astronauts felt much better by 1 August; a telecast to Mission Control showed them at lunch, obviously in high spirits. Bean demonstrated his proficiency at eating while hanging upside down and Lousma reported that "the food tasted a lot better." The meal was one of six the crew ate during the day. Since the astronauts had experienced the most discomfort with full stomachs, Houston doctors recommended more, smaller meals. That afternoon Lousma had only mild dizziness doing experiment M131, and Garriott completed the first run on the ergometer and lower-body negative-pressure device. By evening, the medical office had given the green light for EVA on 4 August.[7]

NASA officials were perplexed by the motion sickness and worried



Bean on the ergometer breathing into the metabolic analyzer. SL3-110-1399.

about its impact on future programs. Individual astronauts had fallen ill on previous flights but never an entire crew. Furthermore the astronauts' response did not match previous performance. Bean had flown to the moon without a symptom, and Lousma had shown a strong resistance to motion sickness in ground tests. While the cause of the illness was uncertain, the possible effects were all too clear. As George Low saw it, "Were we to lose three or four days out of each seven-day Space Shuttle flight because of motion sickness, the entire Shuttle effort would be in jeopardy." After the second mission, the prevention of motion sickness became a top priority.[8]

A RESCUE MISSION?

The crew's first EVA was delayed again on 2 August by a faulty steering rocket that, for a while, threatened the entire mission. Apollo's reaction control system consisted of four independent sets of rockets spaced 90° apart around the service module. Each set had four thrusters, hence the common designation, *quad*. Astronauts fired the rockets singly or in pairs to stabilize the spacecraft's position in orbit or to change velocity; the thrusters could also return the spacecraft to earth if the main service engine failed. It came as a surprise when quad B developed a leak on launch day—the reaction control rockets had been among Apollo's most reliable systems. Skylab procedures, however, provided for spacecraft operations with one quad shut down.[9]

Surprise turned to alarm six days later when temperatures in quad D fell below normal limits. The drop triggered a master alarm, alerting Mission Control and waking the crew. At first the malfunction seemed minor, and the problem was not immediately connected with the first

A tense moment in Mission Control, Johnson Space Center, 2 August 1973. A problem in the Apollo spacecraft threatened to require that the second crew return to earth prematurely. From left: Gary E. Coen, guidance and navigation system flight controller; Howard W. Tindall, Jr., flight operations director; Christopher C. Kraft, Jr., JSC director; Sigurd A. Sjoberg, JSC deputy director. S-73-31875.

day's leak. Crewmen activated heaters in the reaction control system and turned to other duties. During the next hour, Mission Control received positive indications of a second leak: temperature and pressure in quad D dropped sharply and the astronauts reported a stream of sparklers outside their window, similar to the crystals they had seen the first day.[10]

JSC engineers assumed the worst—that the two leaks represented a generic problem in the oxidizer portion of the reaction control system, possibly contamination of the nitrogen tetroxide. If this were true, the other rockets could soon fail. An oxidizer leak could also damage electrical circuits within the service module. Although quad D had lost less than 10% of its oxidizer, there was no telling how fast the leak might expand. The astronauts could maneuver the spacecraft with two quads, or perhaps even one, but it was a situation to avoid if possible. At midmorning the press was informed of the situation's gravity. Skylab's rescue capability, added three years earlier, suddenly looked like a good investment. According to Glynn Lunney, Houston's spacecraft manager, "if we did not have a rescue capability we would be . . . getting the spacecraft down as rapidly as we could."[11]

At Kennedy, the news had an electrifying effect. Within three hours preparations for a rescue were under way. By eliminating subsystem tests at the Operations and Checkout Building, the spacecraft could be mated with its Saturn launch vehicle the following week. At the pad, storage lockers could be removed from the command module to make room for additional couches. Foregoing the traditional countdown demonstration test, the Launch Operations Office expected to have a vehicle ready in early September.[12]

Tensions eased considerably when JSC engineers concluded that the two thrusters did not share a common problem. The possibility of contaminated nitrogen tetroxide was also ruled out after an examination of records at Kennedy. JSC officials believed the two quads were still serviceable; if not, simulator operations indicated that the spacecraft could return safely without them. Kraft notified the crew that EVA would be delayed again, this time so that Mission Control could prepare procedures for reentry with two operational quads. He noted that rescue operations were under way as a matter of prudence, but that "we're proceeding as if we're going to have a nominal mission."[13]

The leaking thrusters pointed up strengths and weaknesses in the Skylab operation. A subsequent investigation attributed the failure in quad D to loose fittings in the oxidizer lines which had gone undetected during two years of tests. When the crisis struck, NASA officials were not certain that the crew could deorbit with only one or two operating quads. Fortunately, Skylab's rescue capability meant that no decision had to be made immediately, and within a few hours the spacecraft's condition had been correctly assessed. The mission continued.[14]

DEPLOYING THE TWIN-POLE SUNSHADE

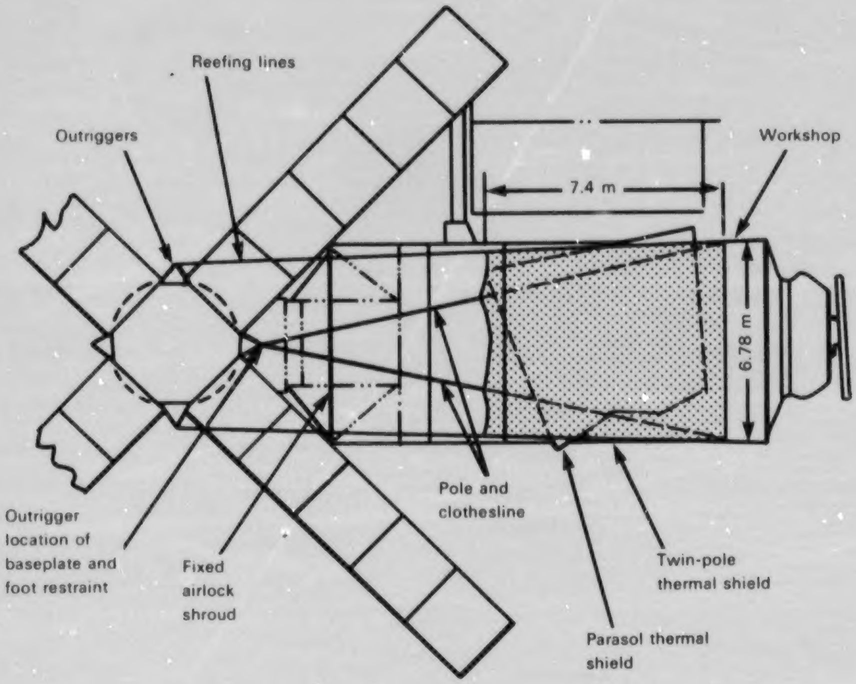
The astronauts had to go outside the workshop for two tasks. ATM film had to be replaced before making any solar observations, and Marshall's twin-pole sunshade had to be deployed before the parasol's nylon disintegrated under ultraviolet radiation. When to replace the original shade had been a question. Bill Schneider and Rocco Petrone had argued for deployment before the first crew left the workshop, but Kraft did not want to subject Conrad's crew to another major extravehicular activity. Medical considerations won out, and the deployment was put off until the second mission. Marshall's design was chosen rather than an improved parasol because it could be deployed over the first parasol. The workshop would not be uncovered even for a few minutes.[15]

Marshall engineers felt confident about their deployment procedure. On this EVA, unlike Kerwin's freeing the solar array, the crewmen would have firm footing. Garriott would begin the operation, positioning himself at the work station outside the airlock hatch. There he would connect the 11 sections of pole while Lousma, working from the mount's center station, secured foot restraints and the shade's base plate to the ATM truss. When the two 17.5-meter poles were assembled, Lousma would attach them to the base plate, forming a V. He would then fasten the sail to rope running the length of the poles and slowly hoist the shade. Bean would monitor the operation from the docking adapter. The crew was well prepared. Besides logging more than 100 hours of EVA training, they had deployed the sail in Huntsville's water tank.[16]

Ample time was scheduled for the operation as one mistake during extravehicular activity could spell disaster. Preparations began on the 5th, the crew reviewing procedures and inventorying hardware. The astronauts spent the morning of the 6th donning their cumbersome suits and testing support systems. Shortly after noon, they depressurized the airlock and opened the hatch.[17]

The work went slowly at first. A rubber grommet, intended to fit over the locking nut on each section of pole, was catching on the storage rack. It took nearly 20 minutes to remove and connect the first three sections, a pace that threatened to extend the deployment several hours beyond schedule. Then Garriott repositioned himself and was able to remove the rods from a different angle. The delay illustrated the problems that frequently arose during EVA when flight articles varied even slightly from the test model.[18]

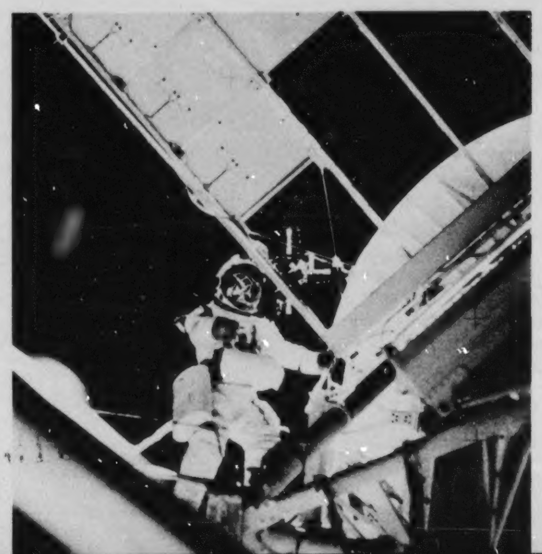
Other difficulties cropped up. The astronauts lost some time trying to untwist the rope before they hit on the idea of separating the pole, passing the line through, and rejoining the pole sections. Lousma ran into further trouble when he began hoisting the shade out along the poles. Folds in the material would not straighten out at once, but with help from the sun's rays, the sail gradually opened. Altogether the deployment ran


Reefing lines
Outriggers
Workshop
7.4 m
6.78 m
Pole and clothesline
Outrigger location of baseplate and foot restraint
Fixed airlock shroud
Twin-pole thermal shield
Parasol thermal shield

The twin-pole shield deployed over the parasol.

nearly four hours; despite minor frustrations, the crewmen seemed to enjoy the exercise immensely. They concluded the EVA by exchanging ATM film, retrieving experiment samples, and looking for evidence of several malfunctions, including the problem with the Apollo quads. When Garriott and Lousma finally reentered the airlock, they had spent 6½ hours outside, by far the longest space walk to that time.[19]

Temperatures in the workshop fell at once. Although the parasol had



Garriott standing on the telescope mount. After helping Lousma deploy the twin-pole sunshade, Garriott attached experiment S149 to one of the solar panels. The experiment was designed to collect dust particles in space and study their impact phenomena. SL3-115-1837.

met immediate needs, its uneven deployment had left some hot spots. At times of maximum sunlight, such as the last week for Conrad's crew, temperatures reached 28° C. This was acceptable during the workday but uncomfortable for sleeping. With the second shade in place, the inside temperatures approximated those originally intended by thermal engineers. Perhaps more important, the successful deployment strengthened confidence in extravehicular activity. Given sufficient preparation, astronauts could accomplish a wide variety of tasks in space.[20]

SOLAR VIEWING

The crew wasted little time getting to work with the solar telescopes. On 7 August, Garriott observed the sun's outer atmosphere, the corona, for three hours. Although there was no prominent solar activity, he filled the air-to-ground channel with questions for the principal investigators. The sun grew considerably more active on the 9th when Garriott photographed a medium-sized flare. The following day, astronomers at the Canary Island Observatory detected an even larger solar event. Word was passed up to the astronauts who were enjoying a half-day of rest. (The crew refused to take a full day while they were behind schedule.) Garriott and Bean quickly manned the telescopes and, during the next hour, filmed an enormous eruption of solar radiation. Afterwards, Dr. Ernest Hindler of the High Altitude Observatory described the coronal transient as "a magnificent specimen of this type," one that would come along only two or three times a year.[21]

Solar observations increased during the next 10 days, reaching a peak of 14 man-hours on the 20th. The hydrogen-alpha telescopes were the principal means to locate solar activity and recognize early stages of flares. *Skylab*'s x-ray and ultraviolet instruments were aligned with the H-alpha telescopes. Thus when an astronaut placed the crosshairs of the H-alpha monitor on a particular activity, he automatically brought the other instruments to bear on the same target. The H-alpha telescopes provided photographs and television, as well as a zoom capability to vary the field of view. A second monitor on the ATM panel presented images from the extreme ultraviolet spectroheliograph. In these wavelengths, some 20 times shorter than the unaided eye could see, the sun appeared blotchy with many bright points, indicating active regions.[22]

The white light coronagraph, developed at the High Altitude Observatory in Colorado, served as the principal means of studying the corona. Four coaxial disks, located at the front of the telescope, blocked out the bright light, allowing only the faint corona to be seen. Although the coronagraph's wavelengths were visible to the naked eye, the instrument provided a view seldom seen on earth; in effect, the crew enjoyed a solar eclipse every hour of the day. Pictures from the coronagraph were recorded on 35-mm film and could be displayed on a console monitor or transmitted to the ground via television.[23]

Two weeks of solar viewing culminated on the 21st with the discovery of a huge solar prominence on the sun's eastern edge. NASA was again alerted by an astronomer working at the National Oceanic and Atmospheric Administration's site in the Canary Islands. At JSC, investigators quickly prepared an observing program for the crew. Meantime Bean had discovered the structure, sitting "like a big bubble . . . on the edge of a disk." During the next several hours, solar scientists watched the prominence—nearly three-quarters the size of the sun—arch outward through the corona as a massive loop structure. Investigators were ecstatic, calling it "the most significant [solar] event since the launch." Bean's judicious use of limited film in the white light coronagraph brought the crew praise.[24]

The second crew's success with the ATM prompted newsmen to contrast the results of the first two missions. At a press conference on 10 August, Hindler acknowledged that operations had improved but credited the change, in part, to Conrad's crew. Their complaints had helped open lines of communication. Investigators enjoyed more access to the second crew, either directly or through the capsule communicator. Consequently, the scientists had "much more rapport with this crew than . . . the last one." Personalities were also a factor; as Hindler noted, "Garriott asks many more questions of us that we respond to."[25]

EARTH-RESOURCE AND COROLLARY EXPERIMENTS

For a week after the EVA, the crew was heavily committed to earth-resource observations. Flight planners had bunched the 26 scheduled earth-resource passes at the start and finish of the 58-day mission; during the middle three weeks poor lighting conditions prevailed in the northern hemisphere. Houston usually scheduled one pass a day, the average run lasting about 35 minutes. Another two hours, however, was taken up adjusting camera settings, replacing film, and loading maneuver parameters into *Skylab*'s computer. (Later in the mission, the crew halved this preparation time.) Unlike ATM operations, where one man worked alone most of the time, earth resources was a team effort. Normally Garriott operated the S190B earth-terrain camera through the anti-solar scientific airlock, opposite the parasol. Bean and Lousma took turns handling the viewfinder tracking system for the S191 spectrometer while the other manned controls at the main display console.[26]

Nine earth-resource passes flown before 13 August met with varying success; the sensors performed satisfactorily, but heavy cloud cover hindered site verification on several runs. The pass on 8 August was typical in its coverage and objectives. Starting off the coast of Oregon, the crew operated the earth-resource cameras for 35 minutes, covering a 13 500-kilometer stretch of land and sea to a point south of São Paulo, Brazil. Objectives included data on Oklahoma's soil moisture, Utah's mineral formations, Houston's urban growth, and the Amazon's resources. At a briefing on the 15th, coordinator Richard Wilmarth expressed satisfaction with the quantity of data. Newsmen, in turn, questioned the three-week gap in operations and the paucity of sites in the southern hemisphere. Wilmarth indicated that NASA was considering additional runs.*[27]

The interruption in earth-resources work gave the crew a chance to do some of the 22 corollary experiments, the catchall title for those relating to space technology, space physics, and stellar astronomy. Bean and Lousma did most of the corollary work, leaving Garriott free to attend the ATM console. Commander and pilot spent the morning of 13 August flying the M509† maneuvering device, a large backpack that NASA hoped to perfect for EVA. Although Bean was generally impressed with the M509, he wanted more speed and less precise attitude control. He stressed the need "to get something that flies like a spacecraft," to ensure that the astronaut's intuitive response was a correct one. In subsequent sessions, the two men tested a hand-held unit fed from a backpack. Bean found the gas pistol unsatisfactory. He said it felt unnatural and would take "too much training time." A foot-controlled unit was judged unsatisfactory for similar reasons. They spent over 75 man-hours flying or photographing the units in action.[28]

Most of the time remaining for other corollaries went to Karl Henize's stellar astronomy (S019) and Dr. Donald Packer's airglow photography (S063). Henize had taught at Northwestern University before joining the corps of scientist-astronauts. His experiment employed a reflecting telescope and prism in combination with a 35-mm camera positioned in the workshop's anti-solar airlock. A crewman would first extend a rotating mirror through the airlock and then focus the telescope. When the desired star field was in view, he would take two or three photographs, the exposure time varying from 30 to 270 seconds. Normal operations took less than one hour but required scheduling the camera work during a night phase of *Skylab*'s orbit. Packer's experiment, developed at the Naval Research Laboratory in Washington, involved camera work from both the wardroom window and the scientific airlock, in reflected light as well as in the dark. His objective was to photograph the earth's ozone layers and the horizon's airglow.[29]

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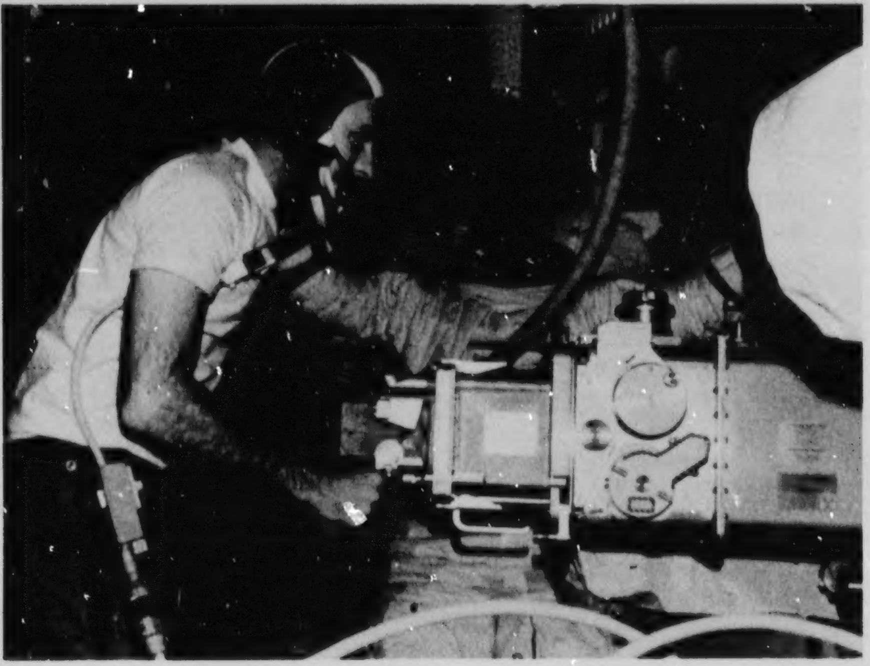
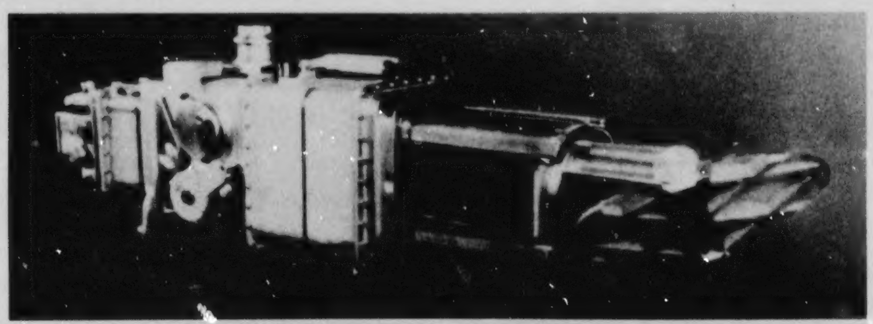
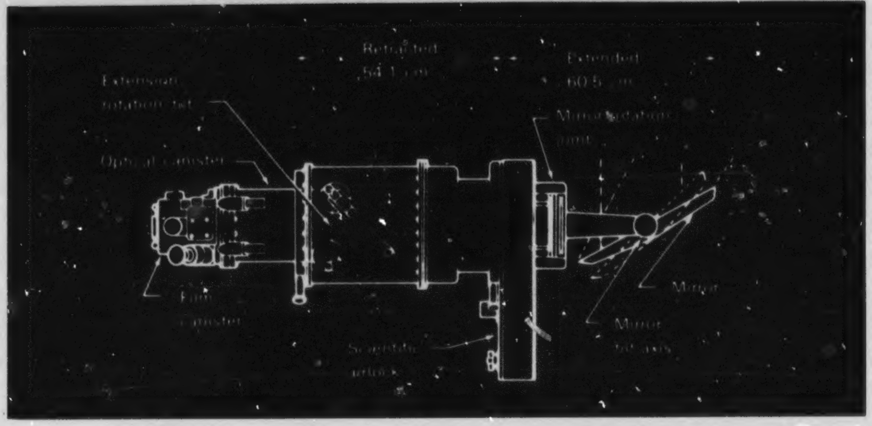
* The drought-stricken region of Mali and Mauritania was added to the schedule in late August.

† App. D contains additional information on all the experiments.



Bean at the antisolar scientific airlock, operating the ultraviolet stellar astronomy experiment S019, above, SL3-108-1275. *Below, the instrument withdrawn from the airlock and a diagram.* S-71-3508-S.




Retracted
54.1 cm
Extended
60.5 cm
Extension
rotation set
Mirror rotation
unit
Optical canister
Film
canister
Scientific
airlock
Mirror
Mirror
tilt axis

More Mechanical Problems

By the second week, mechanical malfunctions had become an unfortunate fact of life for NASA engineers. *Skylab* seemed to be aging rapidly. The dehumidifier's leak remained a constant annoyance. Though not a serious danger, it required daily servicing. On 20 August, Bean spent the entire day inspecting the system; after adding nitrogen, he checked out each connection, listening with a stethoscope and applying a soap solution, much as one does with a bicycle tire. By day's end engineers had concluded that all pipe connections were in good working order. Suspicions turned to the separator plates within the heat-exchange unit. Minor malfunctions seemed to crop up nearly every day. On 20 August, the mechanism used to extend the mirror for Henize's experiment jammed midway out the airlock. Attempts to retract the mirror or fully extend it proved futile until the following morning.[30]

Leaks in the coolant loops were a more serious problem. Two loops cooled the various electronic systems including the controls for the ATM and earth-resources package. On 5 August Huntsville received telemetry indicating a loss of pressure in the primary loop. The signals cast a pall of gloom in George Hardy's office, where engineers already feared a leak in the secondary loop. Contingency plans were quickly drawn up to cover a total loss of the cooling system. By the time Hardy briefed newsmen the next day, matters looked much better. Further data indicated that the primary system would run for another three weeks, at least; the secondary loop would probably last the entire mission. Before the final flight, Huntsville hoped to devise a means of replenishing the coolant.[31]

Erratic gyroscopes were the most troublesome of *Skylab*'s mechanical problems. Huntsville engineers had wrestled with faulty readings from the nine rate gyroscopes since the first launch, three months earlier. From detailed investigation, the gyroscope's high drift rates had been linked with gas bubbles in its float chamber. The bubbles apparently formed when the chamber was exposed to the hard vacuum of space. After correcting the design, Huntsville had prepared a backup package of six rate gyros (promptly dubbed the "six-pack"). It was carried up by the second crew to be mounted, if necessary, on an experiment rack in the docking adapter. The location was close to *Skylab*'s center of gravity, allowed for a proper alignment, and provided an easy tie-in with the old system.[32]

The decision to install the six-pack was a difficult one. Although most of *Skylab*'s nine rate gyroscopes showed some instability, Mission Control had maintained one good gyroscope in each axis, and usually a serviceable backup. Installing the new gyroscope package involved work outside the workshop and failure could possibly end the mission. There was general agreement, however, that a decision should not be delayed beyond the second EVA. Installation on the final EVA, coming just one day before mission's end, would not leave the crew enough time to make adjustments. On 21 August, NASA management opted for the six-pack; the original rate gyroscopes were showing continued deterioration and Houston did not want to face an unmanned period with only one working gyroscope in each axis. The astronauts would install the new gyroscopes on the 24th before replenishing the ATM film magazines. The EVA went like clockwork, and when power was restored, *Skylab* had nine good rate gyroscopes (the six-pack and three from the original group). For the first time in nearly three months, Skylab engineers could employ the redundancy management procedures originally planned for the mission.[33]

A ROUTINE DAY IN SPACE

Sickness and mechanical failures disrupted the flight schedule for 10 days, but after the first EVA, the crew settled into a routine. Reveille came at 6:00 a.m. CST, a loud buzzer waking the astronauts. In the hour before breakfast, they dressed and shaved. There was no real trouble selecting clothes as the astronauts had one standard uniform, brown trousers and turtleneck T-shirts. If too warm, one could convert the trousers to shorts by unzipping the pants legs. During strenuous activity, such as the bicycle run, the astronauts usually stripped to their undershorts. The uniform also included a jacket for the cool temperatures of the airlock and docking adapter. With no provisions for washing the uniforms, they were worn a few days and discarded. The feet proved to be the most difficult part of dressing; astronauts found themselves stretching their stomach muscles as they bent over in zero gravity to put on a sock or tie a shoelace. The clothes received high marks for the most part, although there were some complaints about the shortage of socks and the problem of securing objects inside pockets.[34]

Skylab's waste-management compartment resembled the bathroom of a commercial jetliner in its size, metallic appearance, and even its gurgling noises. The compartment took some getting used to. For one thing, the floor lacked the triangular gridwork common to the rest of the workshop; engineers had provided a smooth surface for easier cleaning. Consequently, it was difficult to get a foothold, and a member of the third crew would complain that "you just ricochet off the wall like a BB in a tin can." Another problem was maintaining control of various toilet articles, which floated away unless anchored. Bean secured his articles to the cabinet with Velcro, a plastic material with interlocking bristles that enjoyed wide use around the workshop. The lack of gravity precluded a conventional sink; hands could be washed from a valve recessed into the wall. Wet washcloths were the principal means of bathing, since a shower required about an hour. The first crew showered once a week and seemed not to mind vacuuming up the excess water. Later crewmen settled for a daily scrubbing with washcloths. The bathroom's size precluded more than one occupant at a time, a limitation which posed some scheduling difficulties in the first hour. Paul Weitz eased the problem by shaving at night; Carr and Pogue of the third crew eventually quit shaving altogether. Bean's team found sufficient time by extending their preparations into the breakfast hour.[35]

At 7:00 a.m. the crew assembled around the wardroom table for breakfast. Parallel bars under the food trays served as a chair of sorts, but the astronauts generally preferred to stand. (Sitting placed a strain on the stomach muscles from the forced bending at the waist.) A typical breakfast included bacon and eggs, bread, coffee, and orange juice. While meals were a definite improvement over Apollo, the astronauts complained that their food was too bland and the menu too regimented. Eating in space had other drawbacks, among them the obvious problem of holding things down. When the lid on a warming tray was opened, invariably a can or two would float away. Silverware and food particles showed a similar tendency to wander. All three crews complained about the size of the utensils. Bean, who was probably the least critical of the nine, found their small size "ridiculous." Gas bubbles in the water supply were another headache. (The air that had been used to pressurize the water tanks could not float to the surface in a weightless condition, hence the bubbles.) Occasionally, when crewmen rehydrated their food, the bubbly water would burst the clear plastic bags, splattering food around the wardroom. The gas also contributed to flatulence, and as a member of the last crew put it, "farting about 500 times a day is not a good way to go." Despite these frustrations, meal times were among the more pleasant hours spent in space. They provided a break from a busy schedule, an opportunity to view the world from the wardroom window or just relax.[36]

Although the astronauts would have welcomed a leisurely hour for breakfast, activities had to be completed before the workday began: setting up the noon meal, checking out spacecraft systems, loading film, collecting and processing urine, weighing fecal samples and leftover food. At times, they found themselves behind schedule before the workday began. On a typical day, Garriott would man the ATM console by 8:00 a.m. Bean and Lousma would undertake a medical experiment or a test of maneuvering units. By mid-morning, the crew might change, Lousma moving to the solar telescopes while Garriott returned to the workshop's lower level for his daily ride on the ergometer. Physical exercise had received short shrift during the first two weeks, but after 10 August flight planners began programming 90 minutes a day for exercise and hygiene. If there were no major experiments or repair work, Bean could perform a corollary. This group provided an excellent means of filling out the workday, since most of them could be done in an hour or two. Solar viewing continued through lunch, the crew eating in shifts. The afternoon brought more experiments. When the astronauts ran out of work, as Bean's crew sometimes did, flight controllers employed a "shopping list" of activities—experiments or repairs that crewmen could undertake with short notice.[37]

Dinner was at 6:00 p.m., after which the crew turned to household chores and a review of the next day's schedule. The latter was time-consuming as it usually involved a number of changes in experiment work, particularly on the ATM. The teletype machine was an improvement over Apollo, when astronauts had copied schedule changes in longhand; but the daily instructions to *Skylab* often required two meters of teletype. Crewmen had trouble just securing the printout to the wardroom table.[38]

During an evening pass over a ground station, the crew transmitted a status report including medical data on eating, sleeping, and exercise. Bean's report on 30 August was typical. After providing totals on water consumption, urine, and ergometer exercise, he noted that the crew had averaged between six and seven hours of good sleep. As for their diets, Bean had added 15 salt tablets to his prescribed menu, Garriott "five salts, peach ambrosia, and jam"; and Lousma, the biggest eater aboard, had added "13½ salts, one cherry drink, one can butter cookies, and substituted one veal and two lemonades for one tuna and bread." Each evening the crew also held a private medical conference with the flight surgeon. The conferences confirmed what was apparent from the status reports; after the initial illness the second crew was adjusting to space quite well.[39]

Planners had hoped the crew would complete the evening chores by 8:00 p.m., leaving two hours for relaxation; but the second crew seldom spent an evening that way. Bean, Garriott, and Lousma virtually ignored the distinction between workday and off-duty activities. Although the first crew had made a point of eating together, the second declined such luxury. One man remained at the ATM console, another reviewed the next day's instructions, and the third grabbed a bite to eat. Dinner usually became a late night snack, eaten 30 minutes before bedtime. If there was not enough time in the day, physical exercise waited until evening. The final solution, and one frequently taken, was to postpone sleep by an hour or two.[40]

If most days were all work and no play, it did not make Jack a dull boy. Lousma kept up a constant banter for his "space fans" on the channel B tape, commenting on everything from the airlock's lack of space to Garriott's tonsorial talents. At every chance he put in a plug for the Marine Corps. Some of Lousma's clowning was captured on film, including an amusing routine with "barbells" in space: after straining mightily to lift the weights from the floor, he soared into space, the bells high over his head. Lousma proved adept on both sides of the camera; his tours of the workshop filmed in early September give an excellent picture of life in space.[41]

Science demonstrations provided Garriott a diversion from the daily grind. Before launch he had planned a series of demonstrations on his weekly holiday. Though most holidays were skipped, Garriott found time to illustrate the effect of weightlessness on water drops, magnets, and spinning objects. In the best tradition of science, one of his most successful demonstrations was a sudden inspiration. While working with a nut and bolt on a student experiment, he decided to spin the nut in space and attract it with a magnet. The result was an impressive display of a spinning object precessed by a magnetic torque. Garriott's demonstrations, though far less important than solar viewing or earth resources, could be easily understood by laymen and for that reason brought Skylab much inexpensive publicity.[42]

Bean appeared to have little need for diversion. The most industrious member of a work-oriented crew, he seldom even took time to look out the window. His chief delight seemed to be adding experiment hours to the record.

A TEAM OF OVERACHIEVERS

The crew had run behind schedule for the first 10 days. After the EVA on 6 August, Bean asked Mission Control how far they had fallen behind. Houston's response bolstered the astronauts' resolve to catch up; as Lousma recalled, "we decided that we weren't going home without doing 100% . . . and more if possible." The turnaround during the next two weeks was striking. Whereas Houston had previously given the crew more than it could handle, flight controllers were soon hard pressed to find enough work. On 12 August Bean asked for more tasks, noting that "we're working less hard at the moment than we were prior to flight." He gently admonished Mission Control to "do a little bit more," because "we've got the ability, and time, and energy and I know y'all do down there." Mission Control did its best to oblige the commander, increasing the daily workload—the time spent on experiments or repair activities—from 8 to 12 hours per man during the third week. By mission's end, the crew had surpassed its experiment goals by 50%.[43]

In early September Bean sought to have their mission extended a week or more beyond the 59-day goal. The request was turned down; Houston's medical office wanted more data before committing astronauts beyond two months. The decision also took into account the dwindling supply of food and film aboard the workshop. By mid-September flight controllers had reduced ATM work to 8 hours a day. The resumption of earth-resource passes filled some gaps, but Mission Control was hard pressed to occupy the crew's time. At a postflight briefing, Bean complained about the lack of meaningful work. "We had good scientific experiments, but . . . not enough to fill the time available." His solution was not to reduce the 70-hour workweek; *Skylab* represented too large an investment for that. Rather, he proposed adding new experiments. Garriott seconded Bean's position, urging the last crew to take more ATM film. The recommendations, and more importantly the pace set by the second crew, convinced flight controllers that a 12-hour day was reasonable. Flight plans for the final mission, fleshed out with new experiments, reflected such standards. The third crew would find it a tough act to follow.[44]

17

The Last Mission

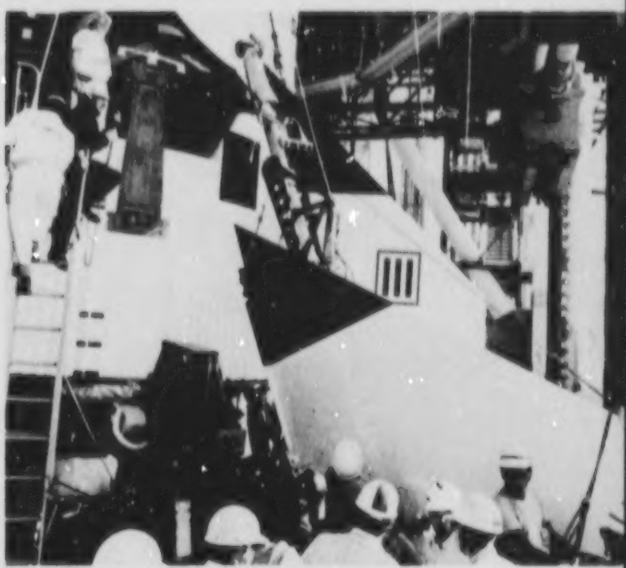
While the second crew set new records for productivity in orbit, the third crew spent long days in Houston's simulators. Bean and his colleagues had enjoyed first priority in using the limited training facilities until they left for the Cape. Only toward the end of July, with just over three months remaining before scheduled launch, did Carr's crew have uninterrupted use of the trainers. Besides practicing rendezvous, docking, and reentry procedures—tasks which took up most of their time—they rehearsed extravehicular activity in Huntsville's big water tank, sat through hours of simulations at the ATM console, and familiarized themselves with the 50-odd pieces of experiment hardware they had to operate.

CHANGES TO THE MISSION

As if this were not enough, mission planners and experimenters devised more tasks for the last crew. After looking at early results, astronomers asked for new solar observations. Medical experts required extra measurements and photographs. Planning for these new experiments was sometimes faulty; the crew would later complain that training for some of them had been totally inadequate.

Late in the summer, Headquarters program officials determined to use *Skylab* as a platform for observing a comet discovered by a Czech astronomer, Lubos Kohoutek, in March 1973. Its early discovery, nine months before perihelion, gave astronomers more time than they normally had to prepare for observing a comet (see app. F). Since the newcomer would swing around the sun in late December, Carr's crew would be in an excellent position to observe it.[1] Using *Skylab* for comet-watching meant that new, complex maneuvering procedures had to be added to the training schedule.

The new experiments were a recognizable addition to the third crew's work load. What no one seemed to recognize was that the second crew had raised everyone's expectations for the last mission. In a press



Removing the first of eight damaged stabilization fins from the Saturn IB that would carry the third crew to Skylab. *The work delayed the launch five days, until 16 November 1973.* 73-H-1105.

conference on 2 October 1973, JSC Skylab manager Kenneth S. Kleinknecht enthused over the second crew's accomplishments, which showed, he said, that man "was able to do more than we thought he could do." Management was retaining the option to extend the last mission to 70 days, and since this would cost around half a million dollars a day, flight planners would have to supply enough work to justify it. The chief of Houston's Orbital Assembly Project Office observed that the remarkable productivity of the second crew was "indicative of what we can expect in the future." The manager of the JSC Missions Office then outlined recent changes to plans for the last flight. There would be 28 man-hours of experiment work per day and 12 new Joint Observing Programs for the ATM. Ten to 14 earth-resource passes had been added to the 20 already planned, and the crew would take some additional medical measurements. Continuing the handyman tradition established on the first two missions, the last crew would recharge the coolant in a refrigeration system and troubleshoot the earth-resources microwave antenna, which had failed.[2]

Throughout October training and launch preparations went smoothly, aiming for a liftoff on 11 November. Five days before that, however, inspection of the Saturn IB launch vehicle disclosed cracks in each of its eight stabilizing fins. The cracks, probably caused by stress corrosion, might well have caused the fins to be ripped off as the rocket passed through maximum aerodynamic pressure early in flight. Replacement fins, flown in from NASA's Michoud, Louisiana, facility, were installed where the Saturn sat, atop the 39-meter "milkstool." Special work platforms, much like painters' scaffolds, were swung from the mobile launcher down to the base of the rocket. The repair crews had to work some 12-hour shifts, but the job was completed on 12 November. Launch was rescheduled for the 16th.[3]

The major uncertainty clouding the third mission was the possibility of motion sickness during the first days in orbit. After the second crew's unfortunate experience, NASA's top managers had become gravely concerned. A group of NASA and outside medical experts, convened in late October to evaluate the data on space malaise, recommended medication upon reaching orbit. After Carr and his crewmates objected, because both of the favored drugs had undesirable side effects, it was agreed that the commander would delay his medicine until after rendezvous was complete. On the second and third days all three astronauts were to take the capsules routinely; thereafter, only if symptoms appeared. They were instructed to restrict head movements as much as possible and to spend the first night in the command module, since moving around in a large space seemed somehow conducive to motion sickness. The astronauts agreed—somewhat reluctantly, because they were not convinced that even the medical experts fully understood the illness.[4]

AN ERROR IN JUDGMENT

Skylab's last mission roared into the Florida sky at 9:01 a.m. EST, 16 November 1973. The launch and early phases of flight were routine, except to the all-rookie crew; on their first pass over the United States, mission commander Lt. Col. Gerald P. Carr told Mission Control that the spacecraft windows were smudged where the three delighted first-timers had been looking out. On the fifth revolution, between Australia and Guam, Carr sighted the workshop; within 10 minutes he had closed to about 30 meters. He maneuvered the Apollo spacecraft in with great precision, but once again the docking gear gave trouble. After two unsuccessful attempts, Carr hard-docked the command module to the multiple docking adapter almost exactly 8 hours after launch.[5]

That done, the crew was out of touch with Houston for 41 minutes between Bermuda and Carnarvon, Australia, so they started straightening up the command module, stowing the gear used during rendezvous and docking. First, however, Carr and scientist-pilot Edward G. Gibson took their antinausea pills. Pilot William R. Pogue had already attended to that, but too late. A few minutes before ground contact was established, he asked Gibson to hand him a vomit bag. Gibson complied, and as he and Carr went ahead with their chores, Pogue said, "I think I'm going to go slow for the next few minutes." It was not enough; weightlessness had done its work, and Pogue vomited—not very much, but he was quite nauseated. Houston came back on the communications circuit just before 6 p.m. and reiterated the physicians' warning about entering the workshop. Before launch, Carr had requested a change of plan to allow them to begin activating the workshop that evening, but flight planners saw no advantage in that. Carr agreed to wait until the next day.[6]

After *Skylab* went out of radio range, Carr and Gibson debated what they should say about Pogue's illness during the evening status report, due in just over an hour. Carr was inclined to keep mum for the time being. To account for the food Pogue had not eaten, Carr would say that Pogue was not hungry. As they prepared their second meal, Carr and Gibson mulled over the situation. It was ironic, because Pogue was noted for his resistance to motion sickness. He was known as "Iron Belly"—the guy with "cement in his inner ear." Cement or no, Pogue was miserable. The others had helped him move to the docking tunnel, where air from a cabin fan might make him feel somewhat better, but he was not improving. When Houston came on the air again, Carr asked to postpone the status report, since they had not started eating. Houston agreed, and Carr had two more hours to decide what to do.[7]

Had they remembered that an onboard tape recorder was running all this time, Carr and Gibson would have reported Pogue's vomiting. But they did not remember; and, thinking that only the three of them would ever know what had happened, they decided to minimize the potential repercussions of the pilot's illness. Pogue had vomited very little; it was not a gut-wrenching attack. Surely he would recover before they moved into the workshop the next morning. Gibson feared that the doctors would overreact if they knew of the vomiting. Carr wavered. He considered reporting Pogue's illness but not the vomiting. "I'd just say he doesn't feel like eating." But a few minutes before the medical conference, he told Pogue, "I think we better tell the truth tonight. . . . Because we're going to have a fecal/vomitus bag to turn in, although I guess we could throw that down the trash airlock and forget the whole thing. . . ." Gibson liked that idea: "I think all the managers would be happy." Vomiting was worse than nausea in the flight surgeons' view, and it would be simple to dispose of the bag and report only that Pogue was nauseated. The distinction was a fine one, hardly worth the uproar that would result if they reported what actually happened. So, as Gibson put it, they could keep the incident "between you, me, and the couch. You know darn well," the scientist-pilot incautiously added, "that every manager at NASA would probably, under his breath, want us to do just that." So, during the medical conference, Pogue's nausea was mentioned but not the vomiting. Before retiring, Carr read the evening status report to the ground, reporting that "the pilot had no strawberries for lunch and has not eaten meal C."[8]

Saturday morning they all felt better after a good night's sleep. Pogue was recovering, but he still chose to take things easy for a while. The others fixed breakfast while enjoying a view of the Alps and south-eastern Europe. At a quarter to nine they were ready to enter the workshop. It took half an hour to pressurize the multiple docking adapter, remove its hatch, and stow both the hatch and the docking probe in the command module. At 9:16 Carr turned on the lights and the crew started to work, hooking up communications, starting up the environmental control system, and powering up the workshop.[9]

Meanwhile, the tapes from the onboard recorder were being routinely transcribed in Houston, revealing the candid discussions Carr and Gibson had held regarding Pogue's illness. Reaction was prompt. A medical conference was called in midafternoon. Toward the end of the day, Alan Shepard, chief of the Astronaut Office, took the microphone in Mission Control to give the crew a public and official, if mild, reprimand. "I just wanted to tell you," he said, "that on the matter of your status reports, we think you made a fairly serious error in judgment here in the report of your condition." Carr accepted the rebuke: "Okay, Al. I agree with you. It was a dumb decision." And that was that. At that evening's change-of-shift press briefing, reporters wondered if the incident portended a break in frank and open communication between crew and flight controllers. Flight Director Neil Hutchinson thought not; but if there were any further signs of lack of candor, he said, flight controllers would immediately take steps to set matters right.[10]

How much this incident contributed to the crew's later problems is uncertain. Managers believed—and the tape-recorded evidence supports their view—that the astronauts meticulously reported on channel B every mistake they made thereafter. They were, however, unwilling to discuss their problems on the public air-to-ground channel. As Carr noted later, they could hardly enjoy having their shortcomings discussed on front pages across the country the next day. And since Pete Conrad's use of the private line for operational purposes (p. 281) had stirred up such a flap within the agency, that route was closed to them except in real emergencies. All they had was channel B, with its built-in time lag of nearly 24 hours before Mission Control could read transcripts of the tapes. Even there (since channel B transcripts were also made public) they hesitated to be completely frank; flight controllers would have had to be finely attuned to the personalities of the crewmen to detect specific problems. That kind of rapport was unfortunately missing on the last Skylab mission; there had been little close interaction between the crew and their flight controllers during training. This helped to produce frustration for all concerned during the next six weeks.[11]

ACTIVATION

Flight control teams, happy to have men back in the workshop after several weeks of unmanned operation, swung back into their routine with gusto. Activating the workshop was the first order of business. Although one flight controller characterized activation as "only a little more complicated than when you come back from vacation," Carr and his crew (like the two crews before them) found it considerably more than that. Every job took more time than anticipated. Inevitably mistakes slowed them down still more, as did communications from Houston; every few minutes an interruption required someone's attention. An hour was lost when Pogue, flushing the potable water system with iodine solution preparatory to tapping a new water tank, left a valve in the wrong position and dumped the disinfectant into the waste tank. By the end of the first day, they were about two hours behind. They did not reduce that deficit the next day. Nevertheless, planners set up a regular flight plan for Monday.[12]

The big job on Monday was to recharge the primary coolant loop that cooled the spacesuits and airlock batteries. Successful completion of this task would permit carrying out the first extravehicular activity as scheduled; without cooling, the outside activities would probably require two trips. Using equipment exactly like that used for recharging ground-based refrigerating systems, Pogue finished that job without trouble.[13]

This repair was only one of several extra chores the third crew had to accomplish during the first week of flight. A particularly time-consuming one was a new set of medical measurements. Girth measurements at more than 50 points on the astronauts' bodies, together with photographs on infrared-sensitive film, would show how blood and body fluids moved toward the head in zero g. The measurements took about four man-hours; the tapes were hard to handle and the crew had not used them at all before flight. The photography would have been easier had there been better provision for restraining the photographer. While the subject lay on the floor of the upper workshop compartment, the cameraman was supposed to float above him. Pogue, trying this for the first time on the fifth day, found himself drifting. Trying to steady his body, he wedged a shoe between two water tanks, accidentally turned a valve and then kicked it off. The resulting loss of pressure was discovered that night.[14]

Tuesday, their fourth day in the workshop, was another jam-packed day; they had no time to look out the wardroom window, although visual observations were on their list of optional activities. Later Carr told Houston, "If we're ever going to get caught up . . . we're going to have to whack something out [of the flight plan] tomorrow. . . . We haven't had time to . . . stow everything properly, and this place is really getting to be a mess."[15]

The first week's big event was the extravehicular activity scheduled for 22 November, Thanksgiving day, when Pogue and Gibson would reload the ATM cameras and check out the inoperative antenna on the microwave sensor. The latter job might be tricky, since there were no restraints on the under side of the multiple docking adapter where the antenna was mounted. But having worked out the procedures in Huntsville's big water tank, the astronauts were confident it could be done.

Just before noon on Thursday, Gibson and Pogue suited up in the workshop's forward dome and squeezed into the airlock. An hour later, after meticulously checking over their gear—stepping out into a vacuum does not allow for careless preparation—they let the air out of the airlock and opened the hatch.[16]

Pogue's first task was to take some photographs to record the amount of contamination surrounding the workshop. He had taken only a few exposures when the camera failed. The shutter speed knob spun ineffectually in his gloved fingers. He then helped Gibson reload the ATM cameras. After finishing that task, they worked their way around the airlock to the inoperative antenna on the earth-facing side of the cluster. They quickly found that, although Pogue had to do the work on the electronics module, Gibson could better restrain himself. So the science-pilot held on to his colleague and moved him around, while Pogue called out directions and used both hands to work.[17]

From telemetry, scientists suspected faults in one or both of the potentiometers that controlled the antenna's oscillations. Pogue opened the module and cleaned the potentiometers; but when Carr applied power to the antenna, it did not function. Some simple tests showed that the problem was in the pitch circuit (controlling fore-and-aft oscillations) and could not be corrected; so Pogue installed a pin to lock the pitch gimbal and a jumper to bypass it. When Carr activated the unit again, it worked, though only side-to-side, scanning across the spacecraft's ground track. Restoring more than half of the instrument's function delighted the experimenters.[18]

Pogue and Gibson returned to the airlock after a 6½-hour, near-flawless exercise. EVA had come a long way since Gemini; Pogue and Gibson had hardly worked up a sweat. Still, it had been a long day, and that evening Carr saw no reason to stay up late to finish the post-EVA checklist. They were tired, and it could wait until Friday.[19]

Next day the astronauts were still behind schedule. Neil Hutchinson told reporters that the crew might get Saturday off, instead of Monday. (Their first scheduled day off, 19 November, had been canceled before launch.) The mission could afford the time, and he thought the crew needed some breathing space. Hutchinson admitted that flight planners had erred in estimating the time needed to get things done and had given the crew too much work to do.[20]

The same problem had come up on the earlier missions, but evidently the hard-charging second crew had left a lasting impression on flight planners, who were trying to bring Carr, Pogue, and Gibson up to the level that Bean, Lousma, and Garriott had achieved. On the first mission, Pete Conrad had been quick to let Mission Control know when he was pressed too hard (p. 288); but Jerry Carr was no Pete Conrad, and no doubt his misjudgment about reporting Pogue's illness had inhibited him still more. He did not want to tell Houston that his crew could not keep up with the flight plan—certainly not on the open communications loop.[21]

A free day on the 24th helped, especially since Mission Control studiously avoided saying anything that might sound like harassment. That evening the commander sat down and reviewed the first week for flight controllers. "The best word I can think of to describe it," he told the channel B tape recorder, "is frantic." Learning to move around "just takes a great deal of time. I think you could tell by our voices that we were very, very frustrated. . . . No matter how hard we tried, and how tired we got, we just couldn't catch up with the flight plan. And it was a very, very demoralizing thing to have happen to us." He was cautiously optimistic; they had finished all the work scheduled through that day, but could easily get behind again. He urged flight planners to give them schedules they could keep up with.[22]

GETTING TO WORK

Sunday it was back to the grind: running the cardiovascular assessment on Gibson, replacing a video display tube and installing a new automatic timer on the ATM console, and checking out the earth-resource sensors. That evening Flight Director Donald Puddy commented positively on the day's accomplishments. The crew's spirits had been lifted by their day off, and he offered the opinion that "within the next few days the comments that . . . we're following a little bit behind the flight plan will disappear from the agenda." Weather permitting, the first earth-resources pass would be made on Monday, and ATM observations were scheduled to start Tuesday.[23]

Flight controllers intended to start a normal work schedule on the 24th. But the day off had postponed that, and on the 23d the workshop sprang a surprise. That night, without warning, one of the control moment gyros heated up and slowed down alarmingly. All indications suggested that an inadequately lubricated bearing had seized up. Flight controllers turned off the sick gyro, switched the workshop computer to two-gyro operation, and began to wonder how they were going to complete the mission.[24]

In normal circumstances the loss of one control moment gyro would have been a minor disturbance; what made it serious was the depleted supply of gas for the attitude-control thrusters. The first few days after launch of the workshop, attitude-control fuel had been used up at an alarming rate (p. 257). When the third crew reached *Skylab*, the system had only about one-third its original capability. Many earth-resource passes remained to be done, and the maneuvers to observe comet Kohoutek would be especially costly in fuel. If there was to be any hope of completing those assignments, flight controllers had to know exactly how much propellant every maneuver would require. Experts at Huntsville and Houston immediately set to work devising more accurate ways to assess the workshop's momentum state and working out new computer programs. All experiments that required maneuvering became much more complicated.[25]

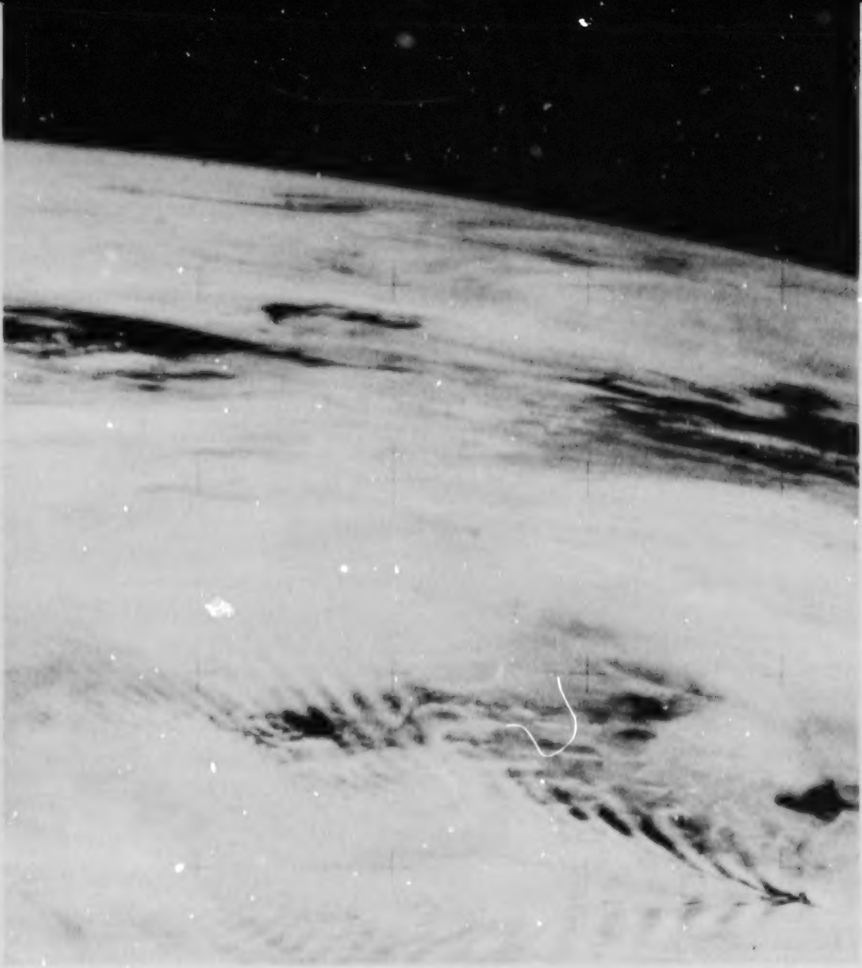
Monday's scheduled earth-resources pass was canceled because clouds covered the site, so the day was given over to a cardiovascular experiment on Carr, stellar spectroscopy, and an observation of comet Kohoutek. Gibson checked out the solar instruments in preparation for the first observing period on Tuesday. It was another busy day, and Carr and Pogue complained of making errors and being rushed.[26]

Tuesday's schedule was typical of the way things would go for the next two weeks. By 6:30 a.m. the astronauts had started their early-morning chores. At 8:22 Carr reported that he had begun ATM operations. Half an hour later, they learned that the observing schedule would be more crowded than planned, since scientists could see considerable solar activity and felt there was a good chance for a solar flare.[27]

While Carr was watching the sun—he had most of the day's ATM duty—Pogue and Gibson had several tasks to perform. Pogue set up a camera in the wardroom window to photograph a cloud of barium vapor released from a rocket, part of an experiment to study the earth's magnetic field. He and Gibson took turns monitoring each other as subjects of the vestibular-function experiment. For the news media, they made a 9-minute TV tape to illustrate in-orbit exercise. Carr explained the ergometer and the "Thornton treadmill" while performing on them. The treadmill was a sheet of slippery Teflon fixed to the floor, on which the astronaut walked in his stocking feet. A bungee-cord harness pressed him down, substituting for gravity. Scientist-astronaut William Thornton had conceived this simple device to stress the leg muscles that were not properly exercised by the bicycle, and it worked very well—so well, in fact, that no one could use it for more than a few minutes. It was a welcome addition to the exercise program.[28]

At intervals during the day, Carr and Pogue took photographs through the wardroom window, choosing sites from a list sent up by Mission Control. This was part of a program to systematize the heretofore informal observation of cloud patterns, ocean currents, and geologic features. Later they would supplement the photography with detailed visual observations and descriptions.[29]

Flight controllers and CMG experts, meanwhile, were learning the limits of their maneuvering capability with two control moment gyros.



A symmetrical bow-wave cloud pattern downwind of small, mountainous Gough Island in the South Atlantic. The island itself, lower right, is clear. The photo was taken with a hand-held 70-mm Hasselblad camera. SL4-137-3632.

Positioning the workshop for Pogue's photography of the barium cloud saturated the CMGs, and considerable fuel was used in returning to solar inertial attitude. Around midafternoon the next day's maneuvers were canceled so that engineers could study the problem a bit more. At the evening press briefing, reporters urged Donald Puddy to estimate how much earth-resources data might be lost, but the flight director was unwilling to concede that any would be. He expected that in a few days the complexities of maneuvering with two gyros would be mastered, so that before the mission was over all mandatory sites could be covered.[30]

After a long day, Carr sat down at 9 p.m. to give the evening status report—sleep, exercise, changes in food and water intake, clothing used, and so on. Ground and spacecraft exchanged several questions and answers about flight plans and the status of systems, and after briefly summarizing the day's news headlines, CapCom signed off shortly after 10 o'clock.[31]

By 30 November the guidance and control experts felt confident that they understood their new constraints. They executed a complicated earth-resources pass that day; the astronauts carried out their part flawlessly and the amount of attitude-control fuel used was very close to what had been predicted. Two days later, however, an attempt to conduct two passes in sequence saturated the gyros and used much more thruster gas than expected. Back to the computers and simulators went the engineers; two more days were needed to devise new procedures.[32]

During the week of 26 November, as flight planners began to step up the pace of the work day, each astronaut responded to a questionnaire about the habitability of the workshop. A question calling for comments on unanticipated problems prompted Carr to reflect on the frantic first two weeks. Most of the unanticipated trouble arose because there was no way to train adequately for zero-g maneuvering. "When you get up here . . . , it's a whole new world. . . . Everything we did took two or three times as much time as we thought it would take. We fooled ourselves." Then he touched on the root cause of their trouble:

> We told the people on the ground before we left that we were going to take it slow and easy on activation, . . . that we were not going to allow ourselves to be rushed. We got up here, and we let ourselves just get driven right into the ground. We hollered a lot about we were being rushed too much, but we did not, ourselves, slow down and say, "to heck with everything else"; and do things just one after the other, like we said we were going to do.

These reflections went unnoticed by flight planners; still trying to get the third crew up to the pace set by the second, they were in no frame of mind to read such comments for what they were.[33] So they pressed on, shortening the time for tasks by degrees, decreasing the time between planned activities, following what they assumed was the crew's increasing proficiency. Flight directors noted several times that crew performance was not yet as high as they had hoped. On 5 December both the flight director and the crew physician professed to see signs that the astronauts were no longer as rushed as they had been, but next day, Carr complained about the schedule for seven minutes. We wouldn't "be expected to work a 16-hour day for 85 days on the ground," the commander told them, "so I really don't see why we should even try to do it up here." The flight director told reporters that night that 27 man-hours per day of experiment work were being planned—an "increase from the nominal," but less than Bean's crew had done.[34]

FIRST MONTH'S ACCOMPLISHMENTS

Program officials reviewed the mission on its 28th day, 13 December 1973, assessing the performance of spacecraft systems and crew and weighing the prospects for completing 84 days. That afternoon at a press conference, Bill Schneider ticked off the mission's accomplishments: 84 hours of solar observations, 12 earth-resource passes, 80 photographic and visual earth observations, all of the scheduled medical experiments, plus numerous corollary experiments, student experiments, and science demonstrations. The astronauts had done three major repair jobs. The principal worries were the solar x-ray telescope, which had a jammed filter wheel, and an occasional sign of distress in one of the remaining control moment gyros—something everyone was watching very carefully. Unless something unforeseen happened, Schneider said, "we're GO for our 60-day mission, open-ended to 84."[35]

Reporters immediately raised questions about the crew. Why were they so slow? Why were they making mistakes? How did they compare with the first two crews? Both Schneider and Kenneth Kleinknecht denied that there was any higher incidence of error on the third mission than on the first two and refused to compare the performance of crews. Hundreds of changes to the flight plan had made the third crew's job much harder. Kleinknecht put some of the blame on people on the ground who had approved so many changes and asserted that Carr, Pogue, and Gibson were doing "an outstanding job." One unidentified reporter then resurrected the vomiting incident and the crew's unguarded discussion, which he called "in effect . . . a coverup." Was Schneider suspicious, he asked, that other matters were being withheld from flight controllers or physicians? No, the program director replied; the channel B tapes were full of admissions of error and the doctors were satisfied that their medical conferences were frank and open. As for any coverup, the true gauge of that first day's discussion was that Carr and Gibson had finally decided that managers would have to know what had happened and had saved the physical evidence. Both Schneider and Kleinknecht warmly defended the crew, and reporters let the subject drop.[36]

No matter how much officials protested, there was a problem; angry comments from each crewman proved the point that very week. On 12 December Pogue complained bitterly to channel B about the tight scheduling of experiments. He had just lost a couple of photographs because he had to set up a camera in a hurry, and addressing the principal investigator he remarked, "this is going to happen again [and again] until the word gets through to the Flight Activities Officers that they're going to have to give us time to get from one point in the spacecraft to another. . . . I don't know how we're going to get this across to [them] unless you [principal investigators] put your foot down and stomp it hard." Two days later Carr complained—again to channel B—in the same vein.

Flight planners seemed to forget that it took time to enter all the changes to checklists that they sent up. "One little [teleprinter message] 3 or 4 inches long represents about 30 minutes of work." Gibson took his turn on the 20th, detailing exactly how his schedule had been knocked awry that morning by a series of small but time-consuming problems. "That's no way to do business," he complained, and went on: "I personally have found the time since we've been up here to be nothing but a 33-day fire drill. . . . I've been engulfed in building blocks rather than being concerned with the quality of the data." He then declared his personal independence from rigid scheduling, stating that he intended to take as much time as he needed to do each job right. If something got pushed off at the end of the day, too bad. "It's going to come down right, rather than on time."[37]

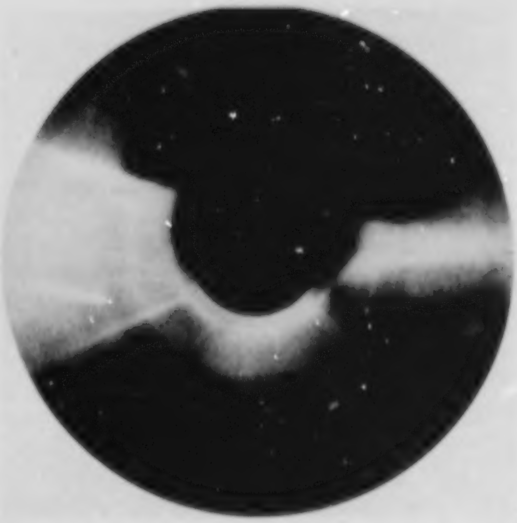
Gibson's comments explicitly expressed something that flight planners had sensed already: the crew could not handle the work load that flight planners were giving them. Program Scientist Robert Parker, an astronaut and astronomer, recalled later that every attempt to increase the daily work load came up against a brick wall at about 25 man-hours. Having indicated that about 30 man-hours would be available when he accepted requirements from the principal investigators, Parker was getting his plans all tangled up. Around the end of the first month he cut back by about 15%.[38]

A COMET FOR CHRISTMAS

As comet Kohoutek sped toward perihelion on 28 December, America's newspapers began a crescendo of coverage intended to climax with the brilliant display they expected around the end of the year (app. F). Scientists and engineers had spent the summer of 1973 working out plans to use *Skylab*'s instruments for comet studies and had developed two new cameras to supplement the ATM telescopes and four corollary experiments already on board.[39]

Systematic comet observations began on 23 November, when Pogue used one of the new instruments, a photometric camera that measured the comet's intrinsic brightness. Observations to collect data on the composition of its coma and tail began two days later. Three corollary experiments and a new electronographic camera measured ultraviolet radiation emitted by hydrogen and oxygen atoms, from which scientists hoped to determine whether Kohoutek contained substantial amounts of ice. These instruments all operated through the antisolar scientific airlock and required maneuvering the workshop to bring them to bear on the comet. By 20 December the crew had made 17 observations with these cameras.[40]

As the comet drew closer to the sun, the solar telescopes became the primary means of gathering data. Because the pointing system was de-



Comet Kohoutek as photographed through the white-light coronagraph, experiment S052. A coronagraph creates an artificial eclipse so that relatively dim objects near the sun can be seen. Here the comet is passing behind the sun, 27 December 1973. High Altitude Observatory photo.

signed to keep the ATM centered on the sun, extra work was required to point it a few degrees away. Two crewmen were assigned to comet observation for the first few days. With only the coronagraph display to provide visual guidance, it was not easy to locate the comet, but after they had run through the new procedures a few times, the astronauts could carry out the complex maneuvers with confidence.[41]

An extravehicular excursion was scheduled for Christmas day, a second four days later. Besides reloading ATM film, the astronauts were to take out two cameras to photograph the comet. There were also two more repair jobs: pinning open a balky aperture door on the ultraviolet spectroheliograph and freeing a jammed filter wheel in the x-ray telescope.[42]

On Christmas morning, after a brief exchange of holiday greetings, Carr and Pogue made the lengthy preparations and stepped out. First, they took a series of exposures of the comet with the coronagraphic camera. Carr then reloaded the ATM cameras and pinned the malfunctioning experiment door open—staying an extra minute or two, at Gibson's insistence, to enjoy the spectacular view from the sun end of the telescope mount. Carr and Pogue then clamped the electronographic camera in place to get some photographs of the comet. Neither could see it, so they pointed the camera at the region where the comet was expected to be and began the prescribed sequence of exposures.[43]

Six hours into the EVA, Carr positioned himself at the center work station on the telescope mount to attempt repair of the filter wheel. It had jammed while his crew was in *Skylab*, so there had been no chance to train for this job on the ground. Using a flashlight and an oversized dentist's mirror, he located the barely accessible filter holder and verified that it was stuck between two positions. Carr then used a screwdriver to push the wheel to an open position, with no filter in place. As he was working his hand into position, Carr momentarily slipped; the shutter snapped shut, and the screwdriver bent one of its thin metal blades. Carr feared he had disabled the instrument and did nothing until he could talk with Houston again—radio contact had faded just as he began to work. When he described the situation to Mission Control, the experiment managers quickly decided to bend the shutter blades out of the way, leaving the aperture fully open. Another 30-minute communications gap came up just as Carr was about to move the filter wheel, and when radio contact was reestablished, he verified the filter position with Houston's telemetry and then pushed the wheel to the open slot. That concluded their scheduled work. When they were back inside the airlock, 6 hours and 54 minutes had elapsed.[44]

On 28 December, Lubos Kohoutek himself came to Houston for a well publicized 11-minute talk with the *Skylab* crew. Neither the astronomer nor the astronauts learned anything from the conversation; it was simply taken for granted that some such gesture had to be made. For the American press, the Czech astronomer had become the important personage of the comet drama, though he was no expert on comets and had only an incidental connection with this one. Seemingly puzzled by the great interest in comet 1973f in the United States, Kohoutek nonetheless went through the public affairs routine, including the conversation with the astronauts, with poise and good humor.[45]

On 29 December, during the third EVA (provided specifically for comet observation), Gibson and Carr finally got a good look at the comet. Gibson gave Mission Control a brief description before the comet passed into the airglow just after orbital sunset. He and Carr then retrieved some samples of materials from outside the spacecraft, set up the cameras to photograph the comet, and made the exposures after they had gone around the earth again. Gibson then provided a more detailed description of the size, orientation, and color of the tail and of the prominent spike stretching out toward the sun. After three and a half hours, the two came back inside, trying to retain their mental impressions of the comet so they could make sketches later. During the next few days the crew spent considerable time observing Kohoutek, using the ATM instruments while it was still near the sun. From 5 January 1974 onward, most of the comet-watching was done with other instruments as the comet headed rapidly away from the sun, to return (perhaps) in 75 000 years.[46]

CARR CALLS FOR AN ASSESSMENT

Aside from one or two complaints from Jerry Carr, the crew said little about workloads and schedules during the last two weeks of December. It had been a busy month, with the extra activity involved in observing comet Kohoutek, but the crew had no trouble keeping up with their work assignments. They even found time to build a crude Christmas tree out of packing material from the food storage cans and decorated it with makeshift ornaments. But crew and ground were not yet marching to the same drumbeat. Flight planners, having mastered the complex art of assembling a day's activity for three men without wasting a minute, were justifiably proud of their expertise and of the quantity of scientific data it could produce. The astronauts, however, did not share that philosophy; they felt their job was to turn out quality results, not merely some arbitrarily large quantity of data. And they chafed under the inflexible scheduling; every tiny housekeeping chore had its bit of time in the daily routine. All three felt that the flight plans were dragging them around by the nose and that the system was not responsive to their needs.[47]

Around Christmas, Carr, Gibson, and Pogue agreed that they had to have a better understanding with the flight planners as to the way things were done. On the evening of 28 December, after sending down the daily status report, Carr remarked to CapCom Richard Truly that he was preparing a special message for Mission Control; he would put it on channel B before he retired for the night. He then went to the onboard recorder and taped a six-minute plea for a frank discussion of the mission's status at the halfway point. "We'd all kind of hoped before the mission," he said, that "everybody had the message, that we did not plan to operate at the [previous crew's] pace." Now he was worried about how his crew was measuring up to expectations. He was puzzled by some of the questions being asked; he had begun to wonder, "Are we behind, and if so how far?" Were flight controllers worried because the crew wanted so much free time? Were they upset by the time the crew wanted for exercise? "If you guys think that's unreasonable, I'd like some straight words on that." Carr assured Houston that he would ask for a private communication if management wanted to talk privately; by now, however, he was ready to talk things out before the whole world. The big question was, "Where do we stand? What can we do if we're running behind and we need to get caught up? . . . we'd like to have some straight words on just what the situation is right now."[48]

Carr later regretted that he had waited so long. "We swallowed a lot of problems for a lot of days because we were reluctant to admit publicly that we were not getting things done right," he recalled. "That's ridiculous, [but] that's human behavior." With that summation both of his crewmates emphatically agreed.[49]

The astronauts were not the only ones who felt they needed a frank exchange of views. Robert Parker recalled that ground personnel too were inhibited by the open communications channel. No one who spoke directly to the crew ever suggested that they were doing less than a great job. "We just very seldom [found] ourselves capable of calling a spade a spade," was the way Parker put it. It got worse when the newspapers began to suggest that the third crew was slower and more error-prone than the second. Everyone in Houston became defensive about the crew, feeling that they were being maligned.[50] Not without reason did Carr call for some "straight words" from Mission Control.

Truly acknowledged Carr's message the following night, and the next day flight planners sent up a long teleprinter message outlining their views and scheduled an air-to-ground discussion for the evening of 30 December. If it took two hours to reach an understanding, everything else could wait.[51]

The importance of the discussion was that it took place at all, although substantive issues were settled as well. One of Truly's first comments was that Mission Control had not been aware of the commander's expressed intention to work at a more deliberate pace than the second crew. Flight planners had indeed tried to push the third crew up to the second crew's level, but when that proved impossible they had cut the load back. To their surprise, however, when flight planners compared the accomplishments of the two missions between the 15th and 30th mission days, they found no significant difference.[52]

Turning to specific scheduling problems, Truly spoke of physical exercise, which Carr felt strongly about. Truly pointed out that the 90 minutes set aside for exercise caused serious scheduling difficulty. The only solution the planners had found was to break it up into two 45-minute sessions. Carr interrupted to give his side of the question: he wanted time to cool down and clean up after a workout on the ergometer, because he despised rushing off to some other job feeling grimy and hot. Doing that twice a day was more than he could take.[53]

Free time was another sensitive issue. All of the astronauts wanted some uninterrupted time after they got out of bed in the morning, and again at the end of the day so they could unwind; this was all the more important because they expected to stay in orbit for 12 weeks. Mission Control was willing to plan for an uninterrupted hour before bedtime, but reserved the option to break into it if a scientific opportunity arose that they could not pass up. "Yes, we appreciate that too, Dick," Carr said; "the reason we started hollering is that there was just getting to be too much of that." "Okay," said Truly, "you asked what some of our flight plan problems are, and that has been one of them."[54]

After nearly half an hour, Truly summed up his end of the conversation with encouraging words. "I think it's important for you to know that we realize that these last couple of weeks, the work load that we've been putting on you is a level that you very obviously have handled with no problems. . . . We naturally would like to continue to get more science per invested hour as we go along"—a hint that Houston still wanted to increase the work load—so "any time you see a consistent gap in the flight planning that provides you a little extra time, believe me, it will help us to know about it. . . . [And] when we go to talk about flight planning . . . , we think it's a lot better to talk about it on the air-to-ground than on the voice dump. . . . so you'll be talking to the team that did it to you, and you guys can have it out." "Okay," said Carr, "we'll sure do it that way from now on."[55]

During the 20-minute communications gap that followed, Carr consulted with Pogue and Gibson and put together his own summation. He still insisted on some quiet time at the end of the day, but said the crew would consider breaking up their exercise periods if that would help. He also suggested that activities that were not time-critical (such as some of the corollary experiments and most of the housekeeping tasks) the crew should do when they could best get around to them. This would allow some judgment and relieve the automaton-like existence they had been leading for six weeks.[56]

Closing the 55-minute discussion, Truly expressed Mission Control's satisfaction. "Jerry, let me say one thing, that [JSC Director] Dr. Kraft and Deke [Slayton, Flight Crew Operations chief] have been here and listened . . . and they're very happy with the way you're doing business, . . . and they think we've made about a million dollars tonight."[57]

Just how much they had actually made was not immediately obvious, but everyone was relieved to find that candid conversations could be held in public without serious consequences. With the assurance that difficulties could be quickly settled and that mission planners were responsive to their needs and preferences, crew morale went up. Why it took so long to reach this level of candor remained a mystery. Many of those involved agreed that ground personnel simply did not realize that the third crew could not be dealt with in the same way as the first two. Jerry Carr—unlike some other astronauts—was not easily prodded into expressing dissatisfaction. Though he vowed before launch that he would blow the whistle if Mission Control pushed his crew too far, his mishandling of Pogue's first-day illness put him on the defensive and made him feel he had to make up for it by producing results. Looking back on it at mission's end, Carr accepted some of the responsibility, but he also faulted flight planners for allowing the crew no time for adjustment. "Obviously [they] were not thinking," he said; "they were just coloring squares and filling in checklists. That is no way to operate a mission."[58]

Afterward, members of the Mission Control team minimized the importance of this discussion—and of the circumstances that led up to it—in the overall success of the last mission. At the time, however, everyone was glad the air had been cleared. Two days later, Flight Director Neil Hutchinson remarked that the astronauts were more alert, that they were looking ahead in the day's flight plan and organizing activities to optimize their work schedule, and that they had stayed ahead of the flight plan all day.[59]

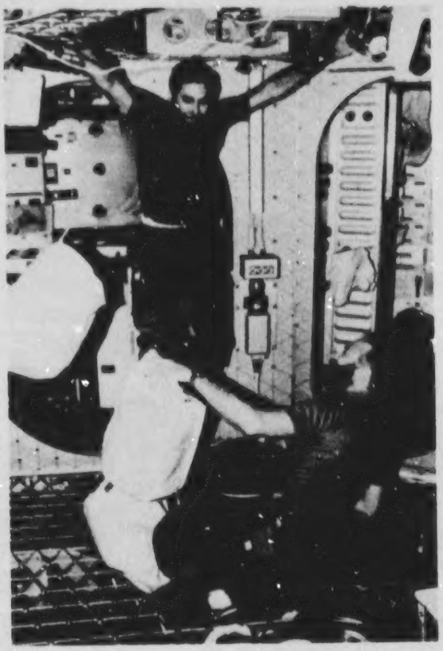
AROUND THE WORLD FOR 84 DAYS

Early in January, Carr, Pogue, and Gibson were closing in on the existing records for duration of spaceflight. On the 4th they eclipsed Pete Conrad's mark—one that had taken four missions to accumulate. On 25 January the first all-rookie crew in eight years would become the world-record holders for time spent in space, but for the time being that title still belonged to the second Skylab crew. The members of the third crew were little concerned with setting new endurance records; that was incidental. Their main interest was in completing the mission planned for them, and, after settling their differences with Mission Control, they went about their work with new enthusiasm.[60]

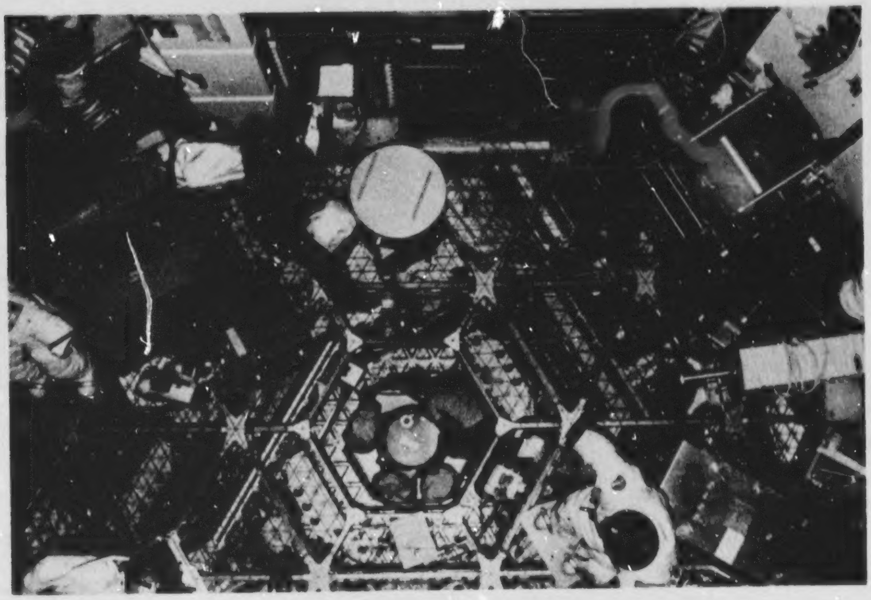
The 10th of January, the astronauts had a day off—which meant that only about a third of their time was formally scheduled. Otherwise they did as they pleased. Gibson spent almost the entire day watching the sun; Pogue and Carr stayed by the wardroom window much of the time, making observations, taking photographs, or simply enjoying the view. Like the earlier crews, they were fascinated by the constantly changing panorama.[61]

Managers, meanwhile, were conducting the 56-day mission review, deciding whether men and machines should be cleared for an 84-day mission. Next day Bill Schneider announced that the word was "GO" for 84 days. Strictly speaking, approval was given only for a week at a time, but little doubt remained that the full 12-week flight could be completed. The only thing likely to curtail it was the ailing control moment gyroscope. Even if that failed, it would create no emergency; the crew would have plenty of time to retrieve the ATM film, pack up their command module, and leave the workshop in orderly fashion.[62]

The gyro, however, was becoming worrisome. Engineers suspected inadequate lubrication of its wheel bearings and conducted maneuvers carefully, trying to reduce stress on those bearings. Toward the end of December they began manually controlling the bearing heaters to keep temperatures in the upper part of the allowed range. This, the experts hoped, would thin the oil and allow it to flow more easily into the bearings. There was not much else they could do. Experiments that required maneuvering the spacecraft now had to be scheduled much more carefully; earth-resource passes had to look exactly right before they were finally put in the flight plan. Weather conditions in late December and early January were not favorable, and earth-resources photography suffered somewhat. Otherwise, at the 56-day milestone the crew was roughly two-thirds of the way through the experiment program.[63]



Bags of trash were deposited in the trash airlock, which had been the liquid-oxygen tank on the S-IVB stage. Toward the end of the third mission, some encouragement was required—which Pogue is prepared, left, to apply. Holding onto the ceiling, he is about to jump on the hatch, so that Carr will be able to insert the remaining bags. S-74-17304. *Below, an unusual view inside* Skylab. *The photographer is near the hatch into the airlock module looking the length of the workshop. The crewman in the center, seen through a passageway in the floor, is stashing trash bags. Two spacesuits and the third crewman are visible on the upper deck.* SL4-150-5061.



The solar observations were closest to being on schedule—in terms of observing time and photographs—but the sun had been fairly quiet. The corona had been active, mostly while the crew was asleep, but general solar activity had been low. Around 10 January, solar scientists expected some active regions to come back into view as the sun rotated. Ed Gibson was particularly anxious for the sun to cooperate. No one had yet photographed a flare from beginning to end, and with only four weeks left, his chances to get one "on the rise" were dropping daily. Early in January, Gibson expressed his desire to spend considerable time in the "flare wait" mode, ready to pounce on pre-flare activity. On 10 January the principal investigator for the coronagraph, Robert MacQueen, conferred with Gibson about strategy for the next couple of weeks. The experimenters wanted more solar activity as badly as the man on the control panel; MacQueen commented, "This is the last time around after more than a decade of this, and we certainly hope the sun cooperates." He gave Gibson permission to change the preplanned programs at his discretion.[64]

After the ATM conference the entire crew took part in a general science conference with experimenters' representatives in Houston. Such conferences were scheduled several times during the mission—usually on the crew's days off—so that experimenters could brief the astronauts on the different science programs, lay out strategy for the next few days, and get their insights into experiment planning.* Specific instructions were sent up daily by teleprinter; the conferences, supplemented by occasional discussions at other times, gave the astronauts an understanding of the scientific objectives and moderated any feeling of isolation between the astronauts and the experiment planners.[65]

For *Skylab* midsummer day came in mid-January, when the position of the earth in its orbit and the high inclination of the workshop's orbital plane combined to keep the spacecraft in sunlight for 46 revolutions. The crew made special efforts to reduce the load on the cooling systems. Mission Control recommended that they not shower during this period to avoid increasing the humidity, but did not insist on it. Workshop temperatures climbed slowly, reaching 28° C on the 18th. Ed Gibson's sleeping compartment was not completely covered by the improvised solar shields, so he moved his sleep restraint into the cooler airlock. This added a constraint to mission operations, since the teleprinter, located in the airlock, was noisy and Mission Control tried to avoid using it while the science-pilot was asleep.[66]

On 20 January, CapCom advised Gibson that observers had seen two subnormal solar flares in one active region in a six-hour period. Later in the day, however, Houston reported that there was little hope anything spectacular might occur. Nonetheless, Gibson thought the region looked promising and watched it for a while. From now on Gibson would be the man on the console most of the time; both Jerry Carr and the scientists wanted to ensure that if anything interesting happened, Gibson would be there to run the instruments. Flight plans were occasionally shuffled and duties exchanged so that he could spend more time at the control and display panel.[67]

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* During the second mission, Mission Control had relaxed a long-standing rule and allowed someone other than CapCom to speak directly with the astronauts.

As far as ground-based observers could see, the sun had changed little by the next morning, but Gibson remained optimistic. Nothing developed during his afternoon watch, but he was so sure a flare was imminent that he offered Carr a bribe to let him stay on the panel for another orbit. Around 5 o'clock, asking Houston for a report on x-ray activity, Gibson said he wanted to spend the next orbit in the "flare wait" mode: "I've already promised the commander some butter cookies when we get back if I could have the orbit." Gibson got the extra orbit—at the price of a bottle of Scotch; the butter cookies were for the benefit of the listening public—but an hour later he was still waiting. Bill Pogue was scheduled to take over the ATM on the next orbit, but when Houston sent up some instructions from the solar scientists, Pogue, tongue in cheek, pointed out a problem: "Ed has the MDA hatch barricaded up there." Gibson stayed at the panel and was at last rewarded. Just before communications broke off he said, "I think this time we finally got one on the rise." He went straight to the channel B recorder and dictated a 23-minute description of the event, repeating it over the air-to-ground when Houston came back. He went to bed that night a happy man.[68]

For the remainder of the mission the ailing gyroscope periodically gave concern. At one point Program Director Schneider ordered the prime recovery ship to prepare for early recovery. But the gyro settled down and at the end was humming along at a reduced speed, still doing its job. The possibility of gyro failure brought *Skylab* back into news prominence briefly, but manned spaceflight was no longer the darling of television. On 23 January the major networks announced that there would be no live coverage of splashdown. It was the first time since live coverage started with *Gemini 6* in 1965 that the networks had intentionally passed up the return of a crew from space.*[69]

The crew held the second televised press conference of the mission on 31 January, in which they confirmed their faith in the value of Skylab and the scientific data collected. As they saw it, the program had proved that man was indispensable to a productive and flexible program of orbital science. Gibson was willing to predict that space stations and manned planetary expeditions, though admittedly far in the future, were clearly possible "when the American people choose to make the effort." When that time came, Carr said, designers were going to have to pay a lot more attention to habitability. Not only was it important to have pleasant quarters and properly designed work areas, but "you're going to have to have a place that you can call home [where you can] be by yourself and do just what you want to do." Asked for comment on the low level of public interest, Carr said, "Well, I think people just get used to things. . . . and take [them] for granted. . . . As long as things stay rather routine in the space program . . . public interest will stay pretty low." The press conference was too short to include four questions submitted by a sixth-grade science class in upstate New York, but since they had been cleared for use, during the next revolution CapCom Dick Truly worked them in one at a time. The student's questions were, if anything, more penetrating than the newsmen's. One that gave Bill Pogue pause was whether the astronaut "felt more of a man now, as compared with before you left?" Pogue begged off the philosophical implications of that one, but did allow that he was a better *crewman*—that is, a more efficient astronaut—after 77 days. Several students wondered whether the three missed female companionship. Taken somewhat aback, Gibson asked, "What grade did you say that was, Dick?" (Nobody had put *that* question so directly before.) Then he answered, "Obviously, yes."[70]

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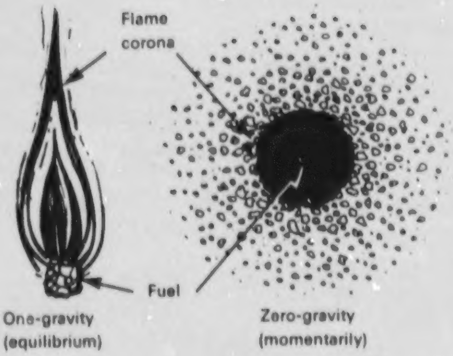
* *Gemini 8*, brought back early because of technical problems, landed far from the primary recovery zone, where TV coverage had been planned.

The first of February was the last full day of experiment work: an earth-resources pass, a set of medical experiments, a final shot of Kohoutek. Next day Ed Gibson finished his last observations from the ATM console. On the morning of the 3d, Carr and Gibson went outside to recover the ATM film carriers and bring in some particle collection experiments. Gibson took a number of photographs, including some to document the condition of the twin-pole sail after its long exposure to space.[71]

COMING BACK

Closing down the workshop and packing the things that had to be returned were big jobs. On the evening of 31 January, Houston sent up a list of changes to the deactivation and reentry checklists; next morning Carr was overwhelmed by 15 meters of teleprinter paper. Entering the changes in the books by hand filled the crew's idle moments for quite a while and provided material for jokes for two days. That evening, Carr greeted Bruce McCandless coming on his shift with, "I understand you're going to teleprinter up the Old Testament tonight."[72]

The major medical experiments continued right on through deactivation, and there were a few experiments left to clean up on 4 February. Carr ran some zero-g flammability tests—put off until the end of the mission because exhausting the residues to space created contamination.



The effect of gravity on flame. In a gravity field, the hot gaseous products of combustion rise by convection, allowing colder air with additional oxygen to enter and mix with the fuel. Without convection, a flame's corona is spherical and the available oxygen is quickly used. The flame dies down until more oxygen becomes available. Experiment M479 studied this phenomenon.

Pogue sandwiched in some observations on light flashes while the workshop passed through the South Atlantic anomaly.[*][73]

The crew had little trouble locating things to take back, but like tourists returning from a long trip, they found some space limitations. Trying to stuff five earth-resource tapes into a command-module locker, Carr could not close its cover, no matter how he rearranged the contents. Before Houston could offer any suggestions, he reported that the overburdened tourist's customary solution worked equally well in space: "It fits if you force it." Gibson had a similar problem with the trays that held the mission's urine and blood samples.[74]

While the crew packed up data and shut down systems, reporters wondered whether NASA planned any more visits to *Skylab*. Neil Hutchinson played down the possibility, pointing out that there would be no atmosphere, no power, and no food. Besides, the workshop systems could be expected to deteriorate beyond reliability. The abandoned *Skylab* would be a drifting hulk, presenting too much risk to make a revisit attractive. He conceded that it would be possible to dock with the workshop, but saw no profit in reactivating and reusing it. Still, just before leaving, the last crew would use the Apollo thrusters to give the workshop a boost, raising its orbit to extend its life by five to eight years. Planners wanted to keep it up until Shuttle missions began, in case someone thought of a good reason to go back—to retrieve some of its components for testing, for example. And the crew would leave specimens of food, clothing, and other articles in the multiple docking adapter for possible recovery to determine the effect of long-term storage in space. The last two nights the astronauts went to bed earlier, shifting their circadian rhythms to suit the planned recovery time.[75]

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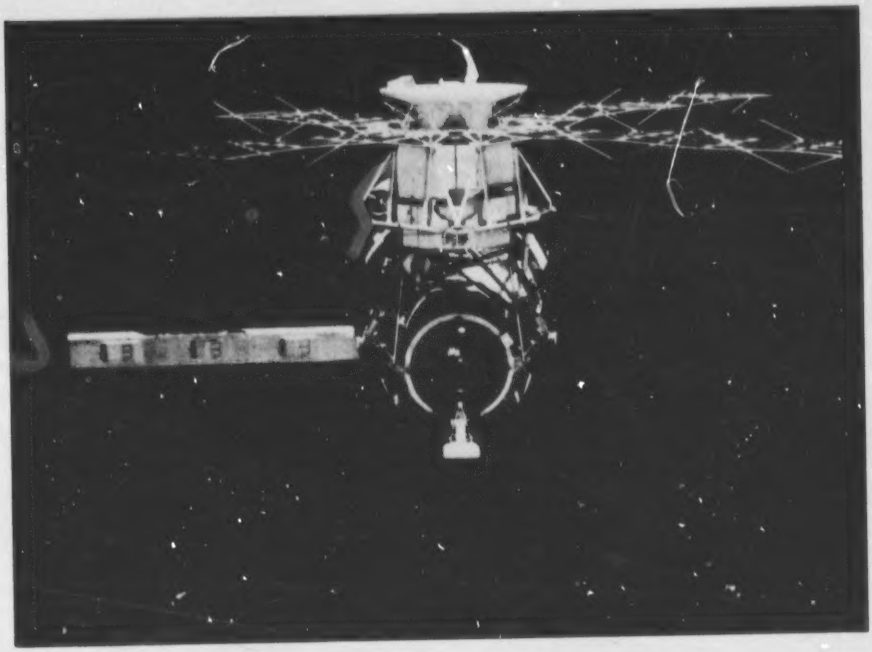
[*] Scientists hypothesized that intraocular light flashes observed on several Apollo flights were caused by cosmic rays expending their energy in the retina. Earlier observations on *Skylab*, however, suggested a correlation with the South Atlantic magnetic anomaly, and Pogue's experiment was done in the hope of confirming that. Strapped in his sleep restraint, he noted the time, direction, and shape of the flashes. He found an abundance of events occurring in the South Atlantic anomaly, and the cosmic-ray hypothesis had to be reexamined. E. A. Hoffman et al., "Visual Light Flash Observations on *Skylab 4*," *Proceedings of the Skylab Life Sciences Symposium, August 27–29, 1974*, NASA TM X-58154, pp. 287–95. In contemporary terminology, the unmanned launch of the cluster was called *Skylab 1*, the manned missions *Skylab 2*, *3*, and *4*.

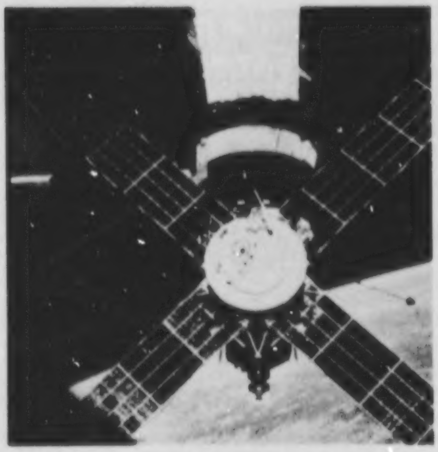
On 8 February 1974, Carr, Gibson, and Pogue moved into the command module and prepared for separation. The subsequent return to earth was normal, with one exception.

At 9:36 Houston time Carr fired the big propulsion engine on the service module, putting the spacecraft on its reentry trajectory. Nine minutes later, when he tried to maneuver the spacecraft with his hand controller, Carr was stunned to find absolutely no response to yaw and pitch commands—the more so since he had checked out all the attitude-control thrusters only minutes before and found everything normal. After a second or two of slack-jawed astonishment, Carr switched to a backup system and gained control. It was later determined that the astronauts had mistakenly opened four circuit breakers, disabling the yaw and pitch thrusters. The incident illustrated the need for maintaining proficiency by repeated simulations during long missions.[76]

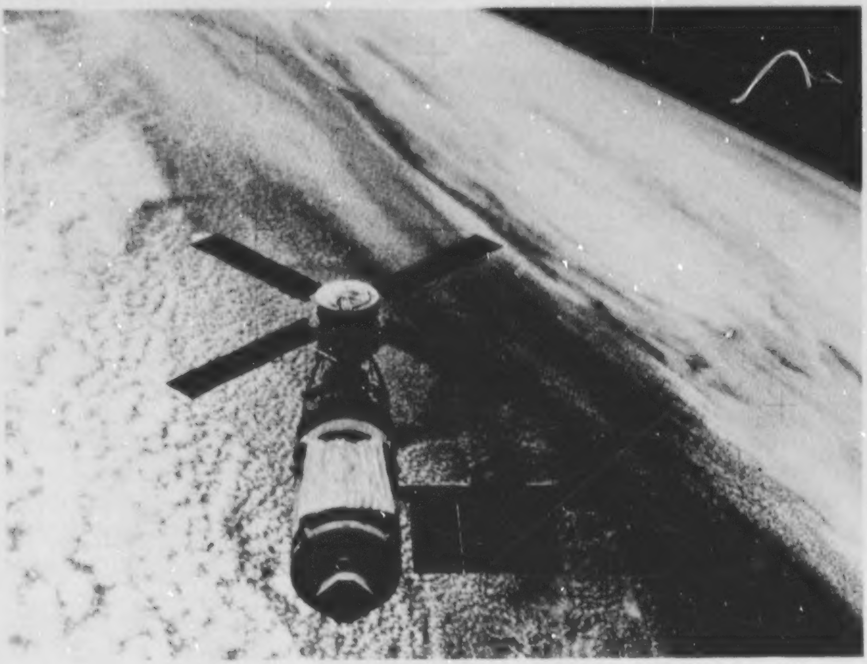
Once in the water, the crew had about half an hour to wait while the recovery crews brought them aboard ship. Nobody was seasick, thanks to

Parting view. The third crew has undocked for the trip home; Skylab *would circle the earth for five more years.* 74-H-96.

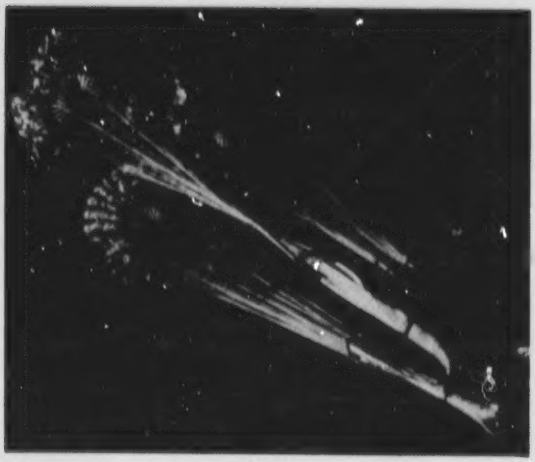




Two views of Skylab *taken by the third crew on the final fly-around inspection. Left, a sun's-eye view of the telescope mount. The lines extending left and right from the hub of the mount are discone telemetry antennas.* SL4-143-4676. *Below,* SL4-143-4706. *In both pictures, the corners of the original parasol are visible on both sides of the twin-pole sunshade.*



the calm seas. What they noticed most was the return of normal gravity. Gibson was acutely aware of the weight of his head and of the effort it took just to move his arms; he felt like he was still in the early stages of reentry. Pogue had taken a camera out of its locker while they were on the chutes and almost dropped it because of its unexpected weight. It felt "like it weighed about thirty-five or forty pounds." After taking one picture of the



Welcome sight to tired astronauts: the three main ring-sail parachutes deployed at about 3000 meters to slow the command module as it approached the water. SL3-114-1760.

parachutes, he had to hold the camera until splashdown because he thought he could not get the heavy thing back into the locker.[77]

While the astronauts went through the first of their postflight medical tests, officials at Houston held the customary press briefing. Administrator James C. Fletcher stressed the importance of Skylab's accomplishments for the future of manned spaceflight: "It has moved the space program from the realm of the spectacular into a new phase that can be characterized possibly as almost businesslike if not yet quite routine." Program Director William Schneider summarized the statistics on the experiment programs; every one, he noted, exceeded premission plans, some by more than 200%. But that was only the start: "Our portion of Skylab has been completed. The science phase has just begun." Skylab had proved that in space research, "the limit is only our resolve, not the ability of men to work, and not our technical knowledge."[78]

As soon as the crew had departed, engineers tested the batteries in the main power system, assessing how much they had deteriorated in orbit. They unloaded and reloaded the ATM's computer memory, something that had not been necessary during the missions, and found that the system worked perfectly. They tried unsuccessfully to start up the dead control moment gyro, then switched off the power to the other two, measuring bearing friction as the wheels ran down. As best the experts could tell, inadequate lubrication was responsible for the failure of number one and the near-failure of number two. On the afternoon of 9 February flight controllers maneuvered *Skylab* into an attitude stabilized by the gravity gradient, with the docking adapter pointed away from the earth, and shut off the power.[79] After the cigar ashes were swept out, Mission Control was quiet.

18

Results

As Schneider had said, the missions were only the first phase of Skylab's science program. Principal investigators immediately began processing the staggering amount of material the crews had collected (table 2). From the five solar telescopes, astronomers had almost 103 000 photographs and spectra (plus 68 000 from the H-alpha cameras); the earth-resource instruments had yielded piles of photographs and kilometers of magnetic tape, dense in detail. Medical investigators had 18 000 blood-pressure measurements, 200 hours of electrocardiograms, and extensive food, urine, and fecal samples for biochemical analysis.[1]

Only a small fraction of this information was available during the missions, most of it medical. Houston's medical directorate had significant operational responsibilities, apart from simply monitoring their experiments. Physicians assessed crew health and health trends daily, using telemetered data, the crew medical conferences, and channel B reports, and continuously advised program managers as to the physical condition of the astronauts. Any unfavorable trends or sudden changes could have curtailed a mission.[2]

The rest of the experimenters had to wait for each crew to return with film, tape, and samples. After each of the first two missions, "quick-look" assessments suggested changes or additions to experiment plans for the next flight. Then the long and tedious evaluations began, to continue for years. Even during the later flights, however, preliminary results were presented to scientific meetings, and by the end of 1974 several major symposia had been conducted summarizing Skylab's results.

MEDICAL FINDINGS

In late August, medical investigators spent three days in Houston discussing the data from all the missions. In the entire program, these were the most important investigations for manned spaceflight; its future depended on man's ability to adapt to zero gravity, to remain healthy

Table 2. Science Accomplishments

Experiment Group	Planned	Actual	Deviation (%)
Solar physics (manhours)	880	941	7
Film (frames)		127 000	
Life science (investigations)	701	922	32
Engineering & technology (investigations)	264	245	−3
Astrophysics (investigations)	168	345	105
Student (investigations)	44	52	18
Materials science & manufacturing (investigations)	10	32	220
Earth observation (passes)	62	99	60
Film (frames)		46 000	
Magnetic tape, various experiment groups (meters)		73 000	

SOURCE: *MSFC Skylab Mission Report—Saturn Workshop,* NASA TM X-64814, 1974, p. 3-39.

while in space, and to return without suffering long-term aftereffects. On the whole, findings presented at this life sciences symposium showed that few serious problems remained.

One that was still troublesome was motion sickness in orbit. Of the nine Skylab crewmen, five became ill in the early stages of flight; only the first crew, plus Ed Gibson on the last, showed no symptoms of motion sickness. (Joe Kerwin, however, was seasick in the command module while awaiting recovery of the spacecraft.) The workshop had carried an experiment to determine sensitivity to motion sickness, a chair in which the subject could be rotated while making rapid up-and-down and side-to-side head motions. On each flight, crewmen were tested periodically. Although on the ground all the astronauts could be brought to the verge of nausea on this device, in flight none could be taken to the same level of malaise.[3]

Motion sickness was so intimately involved with operational considerations that the experimental results were not clear-cut. They seemed to indicate that space malaise was a highly individualistic problem, still unpredictable in any particular case. The drugs used during the program reduced the severity of symptoms, but did not prevent them. All the crewmen, however, adapted within the first week, and illness did not recur for the rest of the mission. Motion sickness was obviously complicated, and Skylab did not provide enough information to understand it thoroughly.[4]

In other areas, investigators were somewhat better served by their experiments. The mineral balance study, while imperfect, showed a clear trend. In space, all crewmen excreted more calcium in their urine, along with a high level of hydroxyproline, an amino acid whose loss is associated with metabolic turnover of bone. This confirmed what had been found during Gemini and indicated a loss of structural material in weight-bearing bones that are subjected to compressive loads in normal gravity. Pre- and postflight x-rays of heel and wrist bones corroborated the mineral balance study. In spite of the third crew's increased exercise, loss of calcium and nitrogen—the latter indicating a loss of muscle mass—continued throughout the mission. The actual amount of bone mineral lost, even after 84 days, was not serious; but that depletion continued unabated implied that longer missions entailed risk. Comparison of the Skylab results with studies on bedridden patients—the nearest one-g analog—indicated the possibility of irreversible damage to leg bones on missions lasting a year or more. Another hazard was kidney stones formed as a result of high concentrations of calcium in the urine.[5]

Results of the several experiments dealing with the cardiovascular system were complex but encouraging. The bicycle ergometer and metabolic analyzer showed that the body's tolerance for exercise did not decrease during flight. Postflight tests, however, showed that adaptation to weightlessness had occurred; astronauts could no longer perform at their preflight levels of physiological efficiency. Readjustment was slowest with the first crew; those astronauts took nearly three weeks to return to their preflight exercise capacity. The others required less than a week.[6]

The lower-body negative-pressure experiment, designed to measure changes in the heart's effectiveness during long exposure to weightlessness, turned out to be more stressful in orbit than on the ground. Results from the first mission had been discouraging; on two occasions Joe Kerwin had been forced to stop his test prematurely. Even after 28 days, crew adaptation seemed minimal. Cardiovascular experts assessed the results and advised continuation of the standard procedure for the next two missions. This decision proved sound. The longer flights showed that after the first 30 to 50 days, astronauts gradually built up a tolerance to the inflight testing. And while the first crew required nearly three weeks to return to their preflight responses, subsequent crews readapted more quickly.[7]

Many of the medical investigations contributed to a picture of what happens to the human body during weightlessness: measurement of leg volume (part of the lower-body negative-pressure experiment), stereophotographs (which enabled calculation of changes in body volume), hormonal and hematological studies, and the infrared photographs and limb measurements that cost the third crew so much time. Before Skylab, aerospace medical researchers had constructed a working hypothesis to account for the physiological changes observed in spaceflight. On entry into weightlessness, body fluids, no longer pulled down by the force of gravity, shifted toward the upper body, producing the distended veins, puffy eyelids, and feelings of nasal congestion experienced by all orbiting astronauts. The body's sensors interpreted this as an increase in blood volume and reacted by altering the hormone balance to stimulate loss of fluid. This triggered a complex set of physiological interactions leading to a new equilibrium (adaptation); among other things, the blood contained fewer red cells, less plasma, and a lower concentration of potassium.[8] Skylab's medical data were not completely consistent with this hypothesis. Blood analyses showed hormone levels lower than expected, along with anomalous levels of electrolytes. More experimental work would be necessary before even a qualitative description of adaptation to weightlessness could be constructed. No physiological changes had been observed that would preclude weightless flights lasting up to nine months, but it was not possible to extend that duration without limit. Much still had to be learned, especially about motion sickness and bone deterioration, before manned missions lasting up to a year could be contemplated.[9]

In a panel discussion that concluded the three-day medical symposium, several outside experts speculated about the meaning of the Skylab results. Most agreed that Skylab had settled some of the major questions about man's survival in orbit and satisfactory readaptation on return. All had ideas for new research or new techniques to be used in future investigations. Imagining a second generation of space laboratories in which only a few occupants would need to be astronauts in the classical sense, one investigator suggested sending up "professional 'subjects'" for laboratory testing. These would be normal individuals who would have no responsibility for managing the spacecraft, so their systems could be allowed to deteriorate in order to test compensatory (preventive or therapeutic) measures. Another, speculating on ways to avoid the consequences of bone loss, believed that the physical qualifications for astronauts might well be changed. Recognizing the need for crewmen to function both in zero g and during reentry, he postulated that "individuals already adapted to something closer to zero g" might have certain physical advantages—"sedentary, skinny, small individuals." This same expert thought that serious consideration should be given to selecting legless amputees as astronauts, since many of the medical problems were associated with legs.[10]

On one point all were agreed: Skylab's medical investigations had raised as many questions as they had answered—always the hallmark of good research. For more answers, the only place to go was back to space. Among all the investigations, only one could effectively be simulated on earth—the mineral balance studies, for which prolonged bed rest seemed to model the space environment adequately.

SOLAR OBSERVATIONS

Astronomers had, if anything, more data than the medical investigators. Cataloging, classifying, and calibrating the thousands of photographs and spectra would take months, and interpretation still longer. Even before the second mission, astronomers began publishing preliminary results; only a month after the first crew returned, researchers at American Science and Engineering submitted a brief description of their x-ray data to a professional journal. Other investigators soon followed.[11] Though the astronomers did not conduct an all-inclusive seminar, as had the medical investigators, assessments of the solar physics programs were made at several professional meetings.

On 3 December 1973, when the third crew had been in orbit only three weeks, Leo Goldberg discussed the significance of some of the early ATM data at the 141st meeting of the American Astronomical Society, where he gave the Henry Norris Russell lecture, entitled "Research with Solar Satellites." Goldberg, director of the Kitt Peak National Observatory in Arizona, had been the original principal investigator for the Harvard solar instrument. In AAP's early days he had clashed with NASA officials over management of the Apollo telescope mount (p. 103) and had been pessimistic about the use of man as an observer in space. Having looked at the early results, however, Goldberg was full of praise for NASA. As things had turned out, the delay in launching *Skylab* (and the improvements delay made possible) had transformed "a mere exercise in manned space flight into one of the most important events in the history of solar physics." The stability of the orbital cluster to 2.5 seconds of arc was "one of the outstanding engineering achievements embodied in *Skylab*." The spatial resolution obtained was certain to bring about a complete revision of solar theories. And as far as the role of man in space astronomy was concerned, Goldberg was a convert. Having doubted that man had any use in orbit beyond adjustment and repair of equipment, he acknowledged that Skylab had proved otherwise.[12]

Goldberg's enthusiasm for the quality of the Skylab results was shared by all the solar research groups. In Los Angeles on 22 August 1974, E. M. Reeves of Harvard College Observatory summarized the accomplishments of the ATM project at the annual meeting of the American Astronautical Society. Reeves noted that all the instruments had equaled or exceeded their expected performance. The photographs from the coronagraph were of a quality and quantity never obtained before. Above all, Reeves was impressed by the flexibility and responsiveness of the experiment management system—that is, operations. One of the remarkable accomplishments of that system during the missions had been a study of the planet Mercury during its transit across the face of the sun on 10 November 1973. The remote-control capability built into the Harvard instrument, together with the rapid transmission of data from remote stations in the communications network, had produced data that would permit an estimate of the density of Mercury's atmosphere.[13]

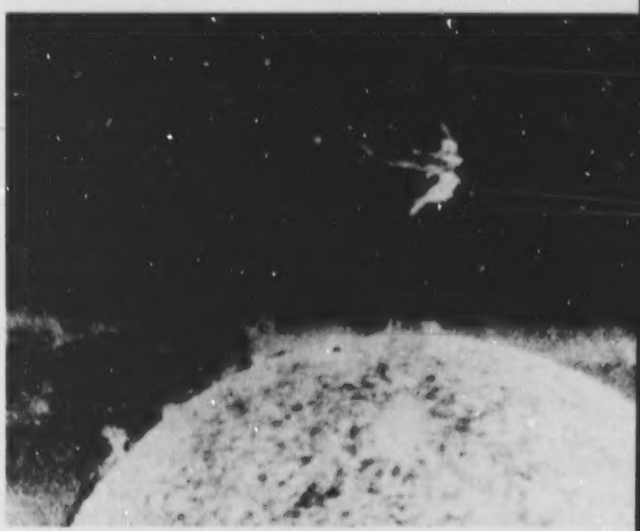
No investigators were more satisfied with their results than the team at the High Altitude Observatory in Colorado. Their white-light coronagraph had shown that the solar corona was far more dynamic than had previously been surmised. Changes in its form and structure were apparent, not only from one day to the next, but over much shorter intervals. During 227 days of observation, the coronagraph (which, like the Harvard instrument, could be operated during unmanned periods), recorded approximately 100 events called "coronal transients." Taking place in a period of minutes, these events sometimes involved the ejection of large amounts of matter and energy into the corona. Roughly half the transients were associated with flares or eruptive prominences.[14]

Everyone who participated was impressed with the intensity and variety of solar activity during a "quiet" period. Although program delays had forced abandonment of plans to observe the sun during its maximum activity in 1969–1970 (p. 103), eight solar flares had been photographed during the three missions. The last, which the astronomers called the "Gibson flare," was recorded from its inception, after Garriott and Gibson had deduced a pattern of solar x-ray activity that preceded major eruptions. Simultaneous use of all the ATM instruments thoroughly documented the evolution of these flares and their relation to events in the corona.[15]

By the end of 1974, solar astronomers were sure that they had the best observations ever obtained from space. Correlation of the x-ray, ultraviolet, and coronagraph observations and interpretation in terms of processes on the sun would take years. Looking back at development problems and ahead to the task of interpretation, Richard Tousey, principal investigator for the Naval Research Laboratory, asked whether it was worth the great effort:

> That it was, would be denied by very few. The solar observations made by the ATM experiments were extraordinarily valuable, perfect, and complete. In spite of innumerable problems, far more than ever imagined possible was accomplished. The solar observations retrieved are staggering in quantity and quality. Best estimates made by each [principal investigator] are that no less than five years of work by competent and sizeable teams are required to reduce and interpret the data, and ten years may well be needed.

Tousey, whose space research started with instruments carried aloft on V-2s in the 1940s, was convinced that unmanned spacecraft could never have come near producing the ATM results. "Skylab has vindicated the use of man in space to perform scientific experimentation, notwithstanding opinions still voiced to the contrary." And after the interpretations, then what? Much would be left to do in solar research, Tousey said; another solar maximum would soon come around, and it would be very worthwhile to fly the backup solar observatory. All but ready to fly, it constituted "a valuable resource that should not be allowed to go to



A huge solar eruption recorded by the extreme-ultraviolet spectroheliograph S082A; helium has been ejected more than 800 000 km. For comparison, the earth is not much larger than the black dot near the rim of the sun and beneath the arch of helium. The instrument was constructed by the U.S. Naval Research Laboratory and Ball Brothers Research Corp. S-74-15562.

waste."[16] There was virtually no hope of that, however, since a second Skylab had long since been ruled out (pp. 116–18).

EARTH OBSERVATIONS

Skylab's earth-resource experiments differed in several ways from the medical and solar experiments. Given the wider variety of instruments, the larger number of investigators, and the diversity of objectives, no clear assessment of the value of the earth-sensing experiments could emerge quickly. Early reports by investigators focused narrowly on individual projects. In the independent but related visual observations program, however—an exercise conducted largely by the third crew—it was possible to assess the value of man as an observer of earth's surface features.

At the Skylab Results Symposium in Los Angeles in August 1974, four teams of investigators indicated the breadth of the earth-resources program and something of the value of the results. A group at the University of Kansas found that the microwave instruments showed promise for measuring soil moisture from orbit. Geologists at the University of Wyoming evaluated the earth-terrain and multispectral photographs for mapping geological and agricultural features. They concluded that the Skylab instruments were, for some purposes, better than those on the Landsat satellite—chiefly because of the better resolution afforded by photographs—but that both had to be supplemented by high-altitude photography from aircraft.[17]

Of more interest were the data returned from the multispectral scanner, which covered 13 wavelength bands in the visible and infrared regions of the spectrum. Investigators at Purdue University used these and the multispectral photographs from S190A in a computerized program of land-use determination; their project aimed at automatic classification of land into nine categories ranging from residential and commercial to grass, farmland, and woodland. By isolating the characteristic spectra of each of these uses, particularly using two or more spectral bands, they could classify land with high accuracy. Skylab's data were roughly as good as those from Landsat's multispectral scanner, which sensed only four wavebands. Similar results were reported by researchers with the U.S. Geological Survey, studying swampland in Florida, and General Electric, looking at geologic features in New Mexico.[18]

Later in the year, similar reports for the other sensors were presented to a conference at Huntsville. Again the multispectral scanner received much of the attention, but geophysicists also reported encouraging results from the radar altimeter. This instrument proved to be able to measure the shape of the earth's surface—more particularly, the ocean's surface—with reasonable accuracy. Perhaps the most impressive result was the detection of local variations in sea level, such as a 20-meter depression near Puerto Rico, probably caused by a local gravity anomaly. The instrument also responded to subsurface geologic features; altimeter data showed clear correlations with the profile of the continental shelf off the coast of Georgia and Florida.[19]

While preliminary results indicated that Skylab's earth sensors had performed as expected and that the investigators had found them useful, wider use of the data was slow in coming. Users seemed content to rely on Landsat, which had been launched in July 1972, possibly because of familiarity with it, but also because Landsat viewed the same ground track every 18 days at the same local time. This repetitive coverage was not available from Skylab. In mid-1975 a NASA-sponsored earth-resources symposium heard 166 reports, only 29 dealing with Skylab results.[20]

The earth-resource experiments did little to establish the value of man in space. Added to the program late, the instruments could not be optimized for man's participation. Apart from tracking assigned sites with the viewfinder on the infrared spectrometer, the operator's main job during a data-gathering pass consisted of punching buttons and recording times and operational sequences on channel B. Judgment as to alternative sites or modes of operation did not enter. On the other hand, astronauts could replace components and do routine maintenance—something the astronomers had felt was absolutely essential, but which their instruments were not designed for. Apart from the major repair job on the microwave antenna carried out by Pogue and Gibson, the crews cleaned tape recorder heads, replaced one tape recorder, and installed an improved detector on one of the infrared instruments during flight.[21]

The value of an intelligent observer for earth observations from orbit was, however, clearly established by the special program developed for the third crew. A team of 19 scientists put together a plan for visual and photographic observations of surface features. This program was only minimally structured; scientists briefed the crew in the most general terms as to the major areas of interest (ocean currents, geology, African drought regions, plus a dozen others) and prepared a book summarizing what the astronauts should look for and what they might expect to see. Some observations were formally scheduled, but much of the program depended on the crew's ability to locate and describe (or photograph) features of interest. During the mission, weekly conferences allowed for modifications and additions to the schedule.[22]

Gazing out the window was a prime recreational activity for the astronauts, and when it acquired a scientific value they enjoyed it even more. With two cameras and an assortment of lenses and film, plus 10-power binoculars, they spent many hours at the wardroom window looking at assigned sites or simply keeping an eye open for something interesting. If the results were not quantifiable, they nonetheless proved what all man-in-space enthusiasts intuitively knew. Man's ability to discriminate, to select the important features of a wide vista, and to respond effectively to unexpected events constituted his greatest contribution to orbital investigations. Following and describing ocean currents for distances up to 3500 km, recognizing upwelling eddies of cold water in warm currents and then discovering the same phenomenon in unexpected localities, waiting for the precise moment to take a photograph—such achievements could not have been programmed into completely automatic sensors.[23]

NASA's Own Experiments

Surveying the results of the habitability experiment, Caldwell Johnson had reason to be pleased with what his group had done for the workshop. Inflight evaluations by each crewman, movies and videotapes made during the missions, and postflight debriefings indicated that no serious mistakes had been made. Still, many aspects of habitability were still to be optimized, and a great many small irritations remained.

Skylab clearly showed that it was feasible to live for extended periods in orbit without becoming disoriented or encountering major problems with the lack of a gravity field. It was simply another work environment, one to which all the crewmen adjusted more or less rapidly. Indeed, they all enjoyed it. Some tasks were actually easier without gravity; moving massive objects, for example, was not hard at all, provided there were adequate handholds to control them. Small objects were more troublesome; hand tools, screws, and other small parts would not stay put.

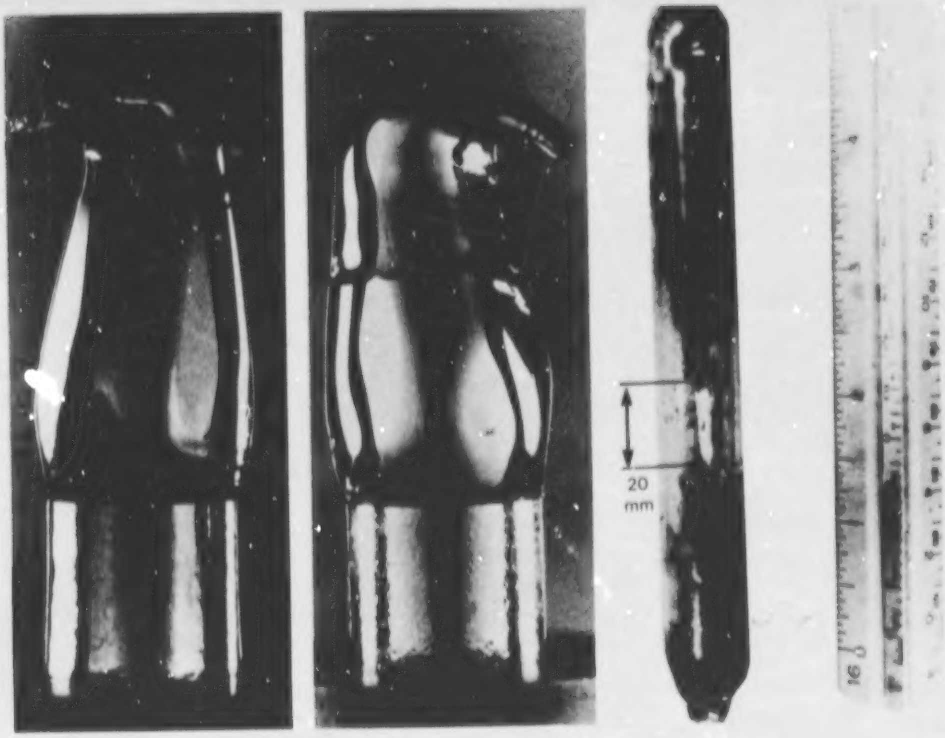
Crews quickly learned, however, that there was little danger of losing something of this kind, because air currents in the workshop would sooner or later carry small objects to the screen covering the intake of the ventilation system.[24]

None of the nine astronauts expressed any strong preference for a uniform architectural arrangement such as that designed into the wardroom and experiment area of the workshop. Although that layout—with a clearly recognizable "floor" and "ceiling"—was an advantage for assembly and testing before flight, once in orbit a uniform up-and-down orientation was superfluous. What was essential was a reference axis at each work station, with all related instruments keyed to a single direction. In the multiple docking adapter, where circumstances had forced a more or less random arrangement of equipment, all the crewmen found they could work easily with any of it. Shifting from one work station to another meant changing the orientation, but this produced no confusion and required only a simple readjustment. Ed Gibson, in fact, gave the docking adapter high marks because it used all the available space with great efficiency, while the workshop wasted wall and ceiling space.[25]

One odd sensation was experienced in the docking adapter by both Jerry Carr and Ed Gibson. Carr noticed that when he entered the compartment from the command module feet first, he had the feeling that he was very high and had to be careful lest he fall all the way "down" to the workshop. Gibson felt the same way when he used one particular foot restraint, which poised him above the airlock hatch. It was the only place in the cluster where he had a sensation of height.[26]

One area in which much work clearly remained to be done was mobility and restraint in zero g. Not surprisingly, this was the area in which exhaustive simulations could not be done before flight; only a few experiments had been simulated in the zero-g aircraft. Mobility was superb and caused no problems, except for the difficulty of controlling the feet when passing through a narrow space, such as the hatch into the airlock or docking adapter. Feet tended to bump into the sides of the passageway, occasionally tripping a switch that was poorly located or inadequately protected. Restraint was the problem; the triangular metal gridwork used as flooring throughout the workshop worked well enough, and the triangular cleats attached to the crewmen's shoes provided good security when locked into it. But in the waste management compartment, where smooth surfaces had been provided for ease in cleaning, it was very hard to hold position. Straps on the floor, under which the feet could be slipped, proved useless.[27]

Many small deficiencies had, of course, shown up in the workshop during flight. Every crew remarked on the need for a workbench where maintenance and small repairs could be conducted. Forced to improvise, they used the ventilation screen in the forward dome, where the air



Crystal-growing in space. The left crystal was grown during the third crew's tenure on Skylab, *the middle crystal during the second. All crystals grown on the second mission showed a ring-shaped groove, probably caused by a spacecraft maneuver during the cool-down period.* From H. U. Walter, *Seeded, Containerless Solidification of Indium Antimonide,* Proceedings of 3d Space Processing Symposium—Skylab Results, vol. 1 (NASA, 1974). *The* Skylab *product on the right, a 20-mm crystal of germanium selenide, was the largest grown on earth or in space as of 1974.* S-74-19677. *Below, NASA Administrator James C. Fletcher explains the process to President Gerald Ford. At the right is Howard Johnson, chairman of MIT.* 74-H-1017.

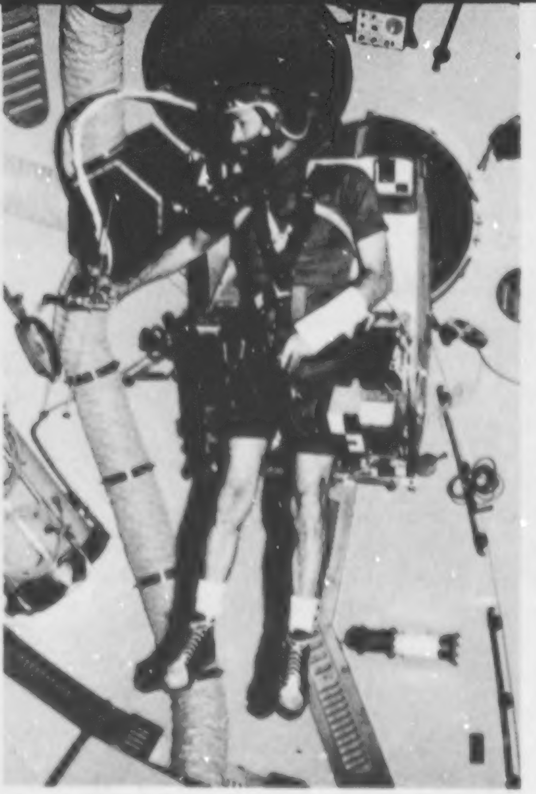
current kept small parts in place, but a properly designed workbench incorporating that feature would have been a great help. Similarly, they found that they needed an office, or at least a desk where they could do their paper work. Stowage also needed considerable improvement. Bill Pogue's bitterest complaints were reserved for the locker numbering system and for the poor latches on lockers and film vaults.[28]

On the whole, however, *Skylab* proved to be well designed for living and working in space; few habitability features were so poorly conceived as to hamper the missions. There had been frustrations, but most of the astronauts learned to work around the workshop's faults. And, as all good experiments are supposed to do, the habitability experiment had shown spacecraft designers the limits of their expertise; it pinpointed the areas where they needed new ideas.

NASA had another major experiment on board, exploring means for controlled maneuvering by a man outside a spacecraft. Apart from one or two tests during the Gemini program, engineers had not experimented with maneuvering aids, and with the approach of the Shuttle era they felt a need to try out some concepts. The workshop's upper dome, 6.5 meters in diameter and about the same in height, was an ideal space in which to conduct tests, and this had been one of the first experiments suggested for the wet workshop in 1965 (p. 27). Skylab tested three concepts for an astronaut maneuvering unit: a large backpack, a small, hand-held gas pistol similar to that used by Ed White on *Gemini 4*, and a foot-controlled unit designed to leave the hands free for work.

The backpack, though bulky, was far more sophisticated than the other two. Fourteen cold-gas thrusters gave the astronaut control over motion along three axes and rotation about three, using a hand controller. Gyroscope stabilization of attitude was available, and small control gyros could be used for rotation. During the second and third missions, five crewmen tested the unit, flying it for nearly 14 hours to give the engineers data on all modes of operation. Owen Garriott determined that operation of the unit was easily learned; having no preflight experience with it, he picked up the techniques of operation in less than an hour. Several potentially useful tasks were performed with the experimental unit. Besides simple point-to-point flying and station-keeping, the astronauts simulated inspection of a spacecraft by flying the unit in a semicircle concentric with the workshop wall and about half a meter away from the upper stowage lockers. Then, after a second crewman had suspended a large object in the upper dome, giving it a slow spin in the process, the operator approached the spinning object, gave himself a rate of spin synchronous with it, grasped it, and used the maneuvering unit to reduce the spin to zero. The technique could be useful in recovering tumbling objects in space.[29]

The two other units, though much simpler, were also less versatile



Carr flying the astronaut maneuvering equipment of experiment M509 in the forward (upper) compartment of the workshop. Two distinct models are involved: the small hand-held unit in Carr's right hand and the large backpack, the controls for which are in the arm rests. Neither proved completely satisfactory. The hatch to the airlock module is behind Carr. S-74-17305.

and therefore less promising for orbital use. The hand-held unit proved too difficult to control accurately; it was hard to produce translational motion without also causing some rotation. While the astronauts felt that it might be useful for short point-to-point movements, it was much less attractive for complex maneuvers. The same was true of the foot-controlled unit. Its thrusters, located alongside the astronaut's feet, could not produce simple linear motion except vertically, and it too tended to cause unwanted rotation. Although the tests on *Skylab* indicated some success with this unit and gave its designers some data, it was clearly inferior to the backpack unit.[30]

COMET OBSERVATIONS AND STUDENT EXPERIMENTS

Among the scores of other experiments carried by *Skylab*, two sets received extensive public notice: the observations of comet Kohoutek and the student projects. Four months after the third crew returned with data on Kohoutek, NASA hosted a symposium at Marshall Space Flight Center to examine these and other results. The *Skylab* observations had been merely a small part of NASA's extensive program to observe this comet. Ground-based observatories, airborne telescopes, and satellites had all been brought to bear, most of them using instruments better designed for the purpose than those *Skylab* carried. While *Skylab*'s instruments produced several useful observations, their contribution was minor compared to the data gathered by the others. The most successful experiments of the *Skylab* group were the far-ultraviolet electronographic camera, which detected a cloud of hydrogen surrounding the comet, and the photometric camera, whose periodic exposures showed that Kohoutek dimmed appreciably after passing perihelion. Sketches and visual observations were among the most interesting data provided from the Skylab program.[31]

In view of their late entry into the program, it was to be expected that the student experiments would produce mixed results. Several were unsuccessful on account of equipment failure, some could not be conducted for operational reasons, and others yielded usable information. A planned observation of Jupiter with the x-ray telescopes had to be canceled because power limitations did not allow the necessary maneuvering. When a substitute observation of an x-ray source in the Veil Nebula was proposed, *Skylab*'s instruments proved to lack the required sensitivity and pointing accuracy. Similar problems foiled two other student investigators: detection of ultraviolet radiation from pulsars and a study of x-rays from stars of different spectral types.[32]

Experiments with living organisms had better luck. Students found differences in bacterial colonies grown in *Skylab*, compared to controls on earth; and rice seedlings exhibited curious anomalies during development. Probably the most widely noticed student project used the web-spinning ability of the common cross spider (*Areaneus diadematus*) to test for adaptation to weightlessness. After dismal failures on their first tries, two spiders taken along by the second crew soon produced nearly normal webs. Owen Garriott wanted to extend this experiment a few more days, but both spiders died shortly after the initial observations—either from starvation or dehydration.[33]

No one would claim that the student experiments produced real advances in science, although their ideas were original and often sophisticated. This was scarcely the point. The project's real effect was on the students and their high school teachers, who were greatly stimulated by NASA's interest in their ideas. The contact with "real world" scientific investigations was an enlightening experience, not only for the winners in the competition, but for all of the competitors. Those who saw their experiments flown sometimes learned that failure is also a possible result of research. For its part, NASA learned that simple experiments, developed at low cost and flown in a short time, can be effective. The poor results of some experiments can be attributed to the lack of adequate training for crewmen and operations personnel, the result of the very busy training schedule.[34]

SKYLAB SCIENCE: AN ASSESSMENT

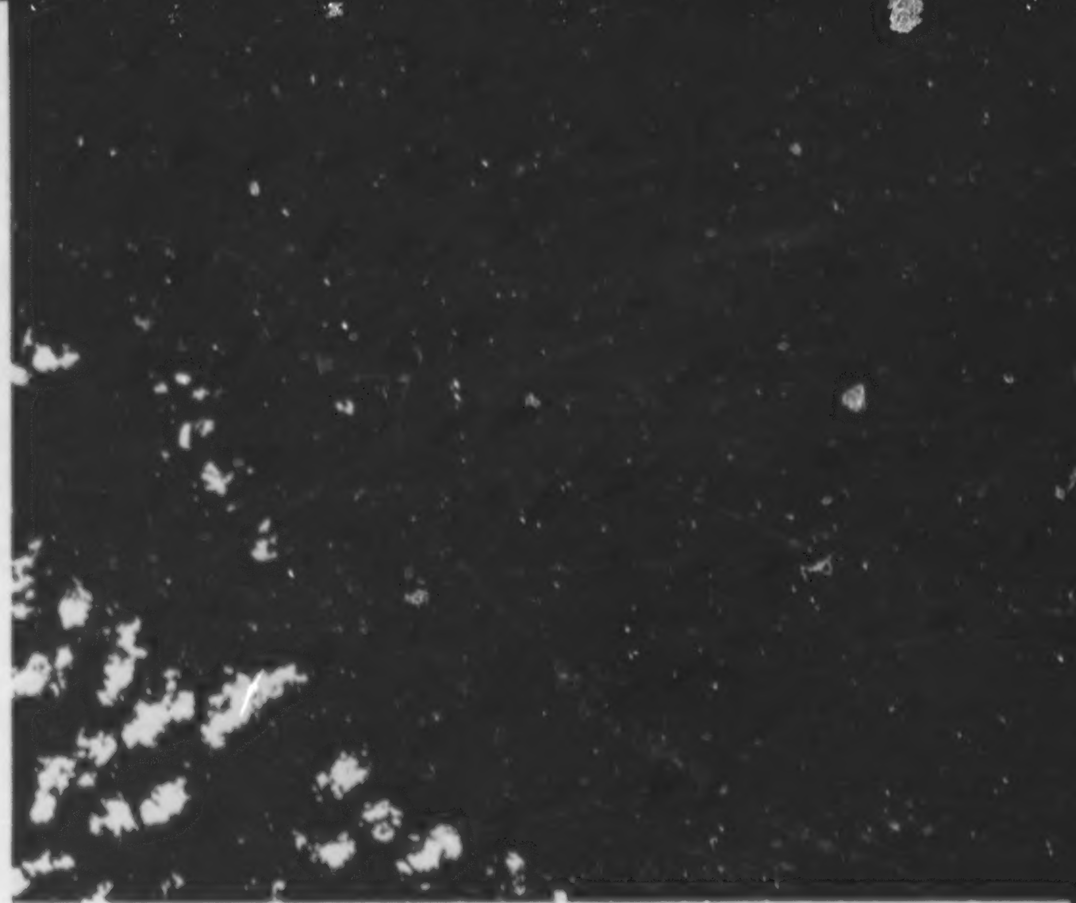
For all the vagaries of its early development, Skylab held to its primary purpose of putting man into orbit to perform scientific work, and in that aim it was indisputably successful. Some scientists even felt that a second Skylab would be justified, even if it did no more than continue the work of the first; but NASA, in a period of shrinking space budgets that forced hard choices, could not afford to plow that ground again. The three Skylab missions cleared the way for the agency to move ahead to the Shuttle. The backup hardware, a fully functional copy of the orbiting *Skylab*, was taken out of storage in 1976 and consigned to the National Air and Space Museum—surely one of the most striking museum exhibits in history.

Skylab's medical results broke down most remaining barriers to extended manned spaceflight by showing that man adapts rather well to the zero-gravity environment, retaining his ability to function effectively for many weeks. Given proper attention to the appropriate environmental factors, he can maintain his physical well-being and morale, then readapt to earth surface conditions with surprising speed. Long-term problems remain unsettled, but these will provide the next generation of research problems. Skylab showed that spacefarers need not be superbly conditioned physical specimens; normal healthy individuals can be taken on orbital missions without risk.

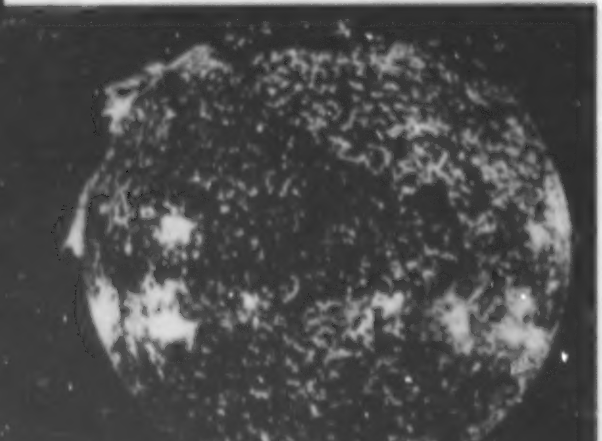
As for man's value as a scientific observer, the point doubtless can be debated whether the money spent on the systems required to sustain man could have been better spent for more sophisticated unmanned equipment. Scientists who participated in Skylab will argue for man. Astronomers who had for years worked with unmanned satellites were won over by the performance of the Skylab crews and ground support personnel. Their ability to react to unexpected occurrences on the sun was a prime factor in the success of the ATM experiments. The same could be said for the earth-observations program; a man in orbit, trained to look for objects of interest and alert for unfamiliar features, proved to be of great value to earth scientists in many disciplines.[35]

In retrospect it seems clear that Skylab's experiment program was just a little too ambitious and heterogeneous. The large number of widely different experiments created operational difficulties, crowded the training schedule, and occasionally led crewmen into errors. While the difficulties were successfully overcome and much valuable experience was gained in the process, individual experiments would probably have fared better had there been fewer of them. But the political atmosphere in which Skylab matured gave managers little choice. As the last manned program for many years, the first multipurpose space station, and the proving ground for man's usefulness in space, Skylab was forced to take on more experiments than was optimum. The earth-resources package and the student experiments are cases in point (chap. 10). The former was a well timed response to an expressed public demand, the latter a way of broadening public support for manned spaceflight, and both paid their way.

Although the specific results of many of Skylab's experiments will not be worked into the fabric of science for a number of years, Skylab clearly established that man has a place in space science. Had it failed, or even left a few key questions unanswered, the future of manned spaceflight would have been bleak indeed. Skylab's success assured that man would not be the limit to the American venture into space.



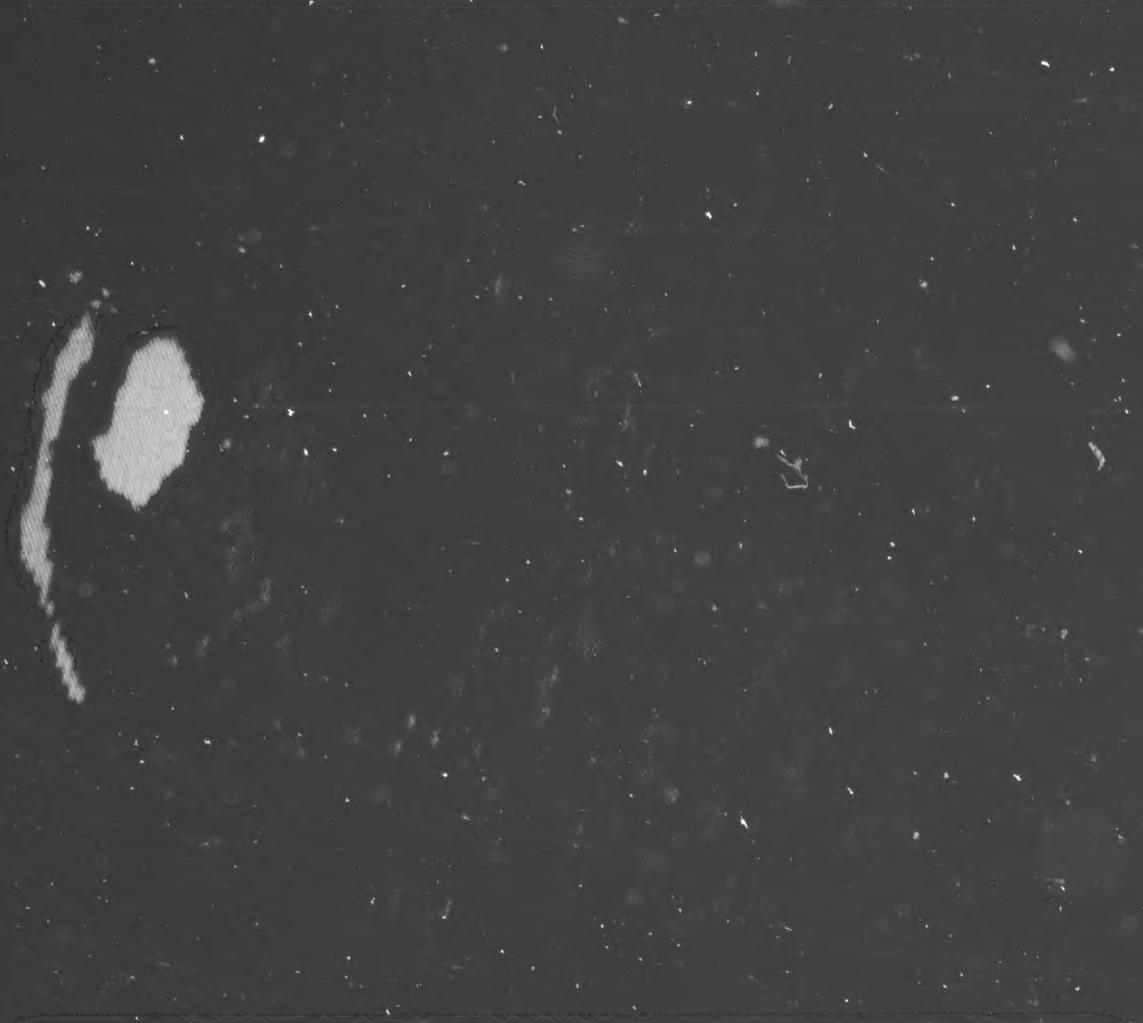
Skylab 4's *view of its starting point, taken with the earth-terrain camera on color infrared film. Launch complexes 39B and 39A, upper left, are connected by crawlerways to the Vehicle Assembly Building. Lining Cape Canaveral itself are older Saturn and Titan complexes. Cocoa Beach is just to the right of the Cape; Patrick Air Force Base runways are visible farther down the coast. SL4-93-167.*



A spectacular solar flare photographed by the third crew 19 December 1973 in the light of ionized helium, using the extreme-ultraviolet spectroheliograph of the U.S. Naval Research Laboratory. The twisted sheet of gas spans 588 000 km and seems to be unwinding itself. The darker areas at the top and bottom are the solar poles. 74-HC-260.

X-ray photograph of the solar corona, 28 May 1973. The corona is the thin outer portion of the sun's atmosphere. Areas hotter than one million degrees can be observed in x-rays. The loops and arches are produced by the interaction of the sun's magnetic field and the ionized gas of the corona. S-73-31696.

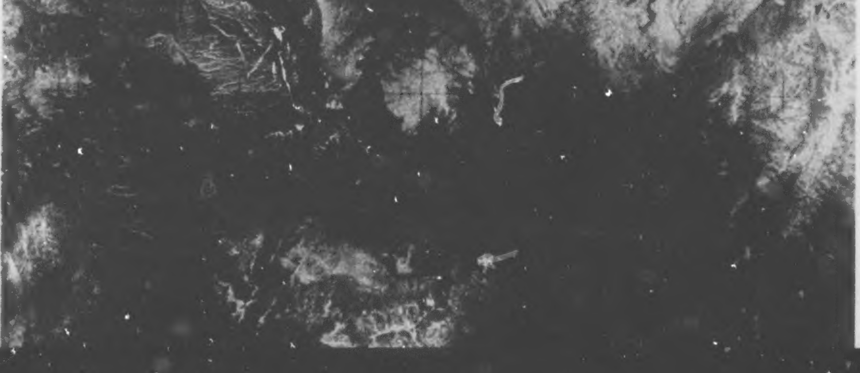
The sun photographed at a wavelength of 625.3 angstroms through Harvard College's spectroheliometer. The black areas are the surface of the sun; the reds, yellows, and whites are the corona some 70 000 km above the surface. The picture is one of a set studying active regions. S-74-21923.



This image of the sun in the extreme ultraviolet was transmitted from Skylab *to Houston, where computer reduction added the color contours and gave it a needlepoint character. The black area starting at the north pole and extending well into south latitudes is a large coronal hole, an area where temperature and density are unusually low. Data collected with* Skylab *instruments established, beyond doubt, that coronal holes are the source of the high-speed streams of particles (the solar wind) that buffet the earth's upper atmosphere, disrupt the magnetic field, and cause other effects in the lower atmosphere.* S-73-32884.

S190B photograph of the Black Hills (lower left) and Badlands (lower right) area of southwestern South Dakota. The Cheyenne River meanders across the right side. Rapid City and Ellsworth Air Force Base are adjacent to the Black Hills. The rectangular patterns are caused by the practice of dry-lands strip farming. The light areas produced crops—mostly wheat—the previous year; the dark areas are the current year's growing crops. SL2-81-159.

Remarkably detailed photograph of the Grand Canyon area of northern Arizona. The high sun angle, light snow cover, and excellent visibility combined to give a picture of unusual value to the geologist. Only a few of the abundant lineations, which indicate faulting, joining, and monoclinal flexing, were shown on contemporary geologic maps of the area. SL4-142-4436.

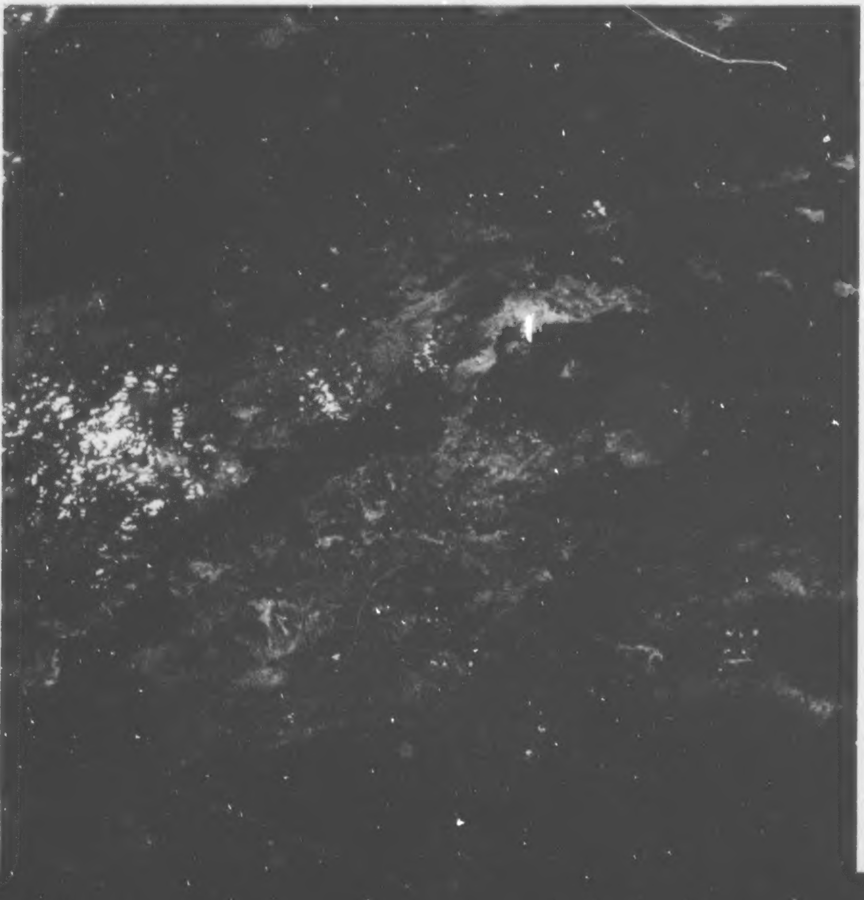


Plankton bloom (upper right) in the South Atlantic, 25 December 1973. Off the east coast of South America, the south-flowing Brazil Current meets the north-flowing Falkland Current near 40° south latitude, where both turn eastward. The light area across the middle of the photo is the boundary between the two. Skylab *crewmen followed the boundary visually more than 3500 km. The pink formation in the lower left is clouds.* SL4-137-3721.

Two smoke plumes stretch some 140 km across the Gulf of Mexico from the central Louisiana coast, 7 December 1973. The value of such photographs in studying diffusion of pollutants is obvious. SL4-136-3475.

Marshes of Dorchester County, Maryland, photographed in color-infrared by S190A in June 1973. Land-use maps can be compiled and the relative salinity of bodies of water can be determined from such imagery. SL2-15-174.

Birthplace of Western civilization, as seen from one of its highest technological achievements. The photograph was taken with a 70-mm Hasselblad camera, 100-mm lens, and medium-speed Ektachrome film. SL3-121-2385.



19

What Goes Up . . .

Before undocking from *Skylab*, Gerald Carr had fired Apollo's attitude-control thrusters for three minutes, nudging the cluster 11 kilometers higher, into an orbit 433 × 455 km. After the crew had returned to earth and the end-of-mission engineering tests were finished, flight controllers vented the atmosphere from the workshop, oriented the cluster in a gravity-gradient-stabilized attitude with the docking adapter pointed away from the earth, and shut down most of its systems. *Skylab* could still respond to telemetry signals whenever its solar panels were in sunlight. A suited astronaut could enter it—assuming he could reach the hatch and had some reason to go inside.[1] But no plans contemplated such a visit or any other reuse of the huge hulk. With one control moment gyro inoperative and another ailing, with two coolant loops behaving erratically and several of the power-supply modules approaching the end of their expected life spans, the $2.5-billion orbiting laboratory was junk.

It was, in fact, inexorably headed for a flaming death in the earth's atmosphere. Calculations made during the mission, based on current values for solar activity and expected atmospheric density, gave the workshop just over nine years in orbit. Slowly at first—dropping 30 kilometers by 1980—and then faster—another 100 kilometers by the end of 1982—*Skylab* would come down, and some time around March 1983 it would burn up in the dense atmosphere.[2] If, as planners hoped, Shuttle development went smoothly, one of the new craft's early missions would attach a propulsion module to the workshop to boost it into a higher orbit. If not, the 75 000-kilogram cluster would probably attract more public attention than NASA wanted when it returned to earth. Flight controllers could do little to change the course of its reentry.

PLANS TO SAVE THE WORKSHOP

The nine-year lifetime of the orbiting laboratory seemed ample in 1974, and in any case NASA had more pressing problems to worry about.

During the next three years the agency's annual budgets shrank to record low levels, delaying the development of Shuttle. Meanwhile the Russian manned program showed every sign of vitality. Soviet cosmonauts surpassed Skylab's endurance records, and Soviet space officials spoke of establishing permanent stations in earth orbit.

By early 1977 the first Shuttle orbiter *Enterprise* was being prepared for landing tests, and planners could begin to think about payloads and missions. Early in the year Headquarters directed Johnson Space Center and Marshall Space Flight Center to outline schedules and funding requirements for a Shuttle mission to boost *Skylab* into a higher orbit. Houston was not optimistic. Problems of rendezvous and docking with the inert workshop had not been thoroughly studied; and JSC's studies showed that a visit to *Skylab* could not be carried aloft earlier than the fifth test flight of the Shuttle orbiter, expected to be launched in late 1979. As the next solar maximum approached (1980–1981), it was becoming clear that the sun was considerably more active than anyone had predicted three years before—bad news for *Skylab*, because solar activity heated the earth's upper atmosphere, increasing its density at orbital altitude and dragging the workshop down faster than anticipated.[3]

Marshall's experts told Headquarters in March 1977 that a study contract to define the booster stage for the *Skylab* mission should be awarded not later than midyear. Headquarters then set the fifth test flight as the target mission and 1 September as the latest date for decision. This would allow just over two years for hardware development. Meanwhile the centers continued to compile the data necessary to make that decision.[4]

In September the word was GO, and in November Marshall awarded a $1.75 million letter contract to Martin Marietta Corporation to conduct analysis and design studies for a teleoperator retrieval system to be carried in Shuttle's cargo bay and used to attach a propulsion module—also still to be designed—to *Skylab*'s docking port. Since time was critical, developed and qualified hardware was to be used to the extent possible—very much in the Skylab tradition. A preliminary design review was set for March 1978.[5]

Within a month, however, this schedule seemed inadequate. A meeting of the American Geophysical Union heard in December from Howard Sargent, chief forecaster for the National Oceanic and Atmospheric Administration (NOAA), that the current sunspot cycle was the second most intense in a century. Sargent's forecast was based on a model different from that used by NASA; he (and others) criticized the space agency for using what he considered to be an inaccurate model. Asked by journalists whether he thought the *Skylab* reboost mission would succeed, Sargent offered the opinion that NASA was "in a pile of trouble" if it was counting on the cluster to stay in orbit long enough for Shuttle to reach it on the current schedule.[6]

Critics of manned spaceflight tried to make capital of the discrepancy between NASA's predictions and those of NOAA, but in fact no single method of predicting sunspot activity was universally accepted by solar scientists. (Ironically, Skylab's own results—unavailable in 1974—would eventually contribute to refining those methods.) All were based on analysis of historical data. NASA's scientists used more observations and predicted less sunspot activity than their counterparts at NOAA. Sargent and his colleagues insisted that some of the very early (17th century) observations that NASA used were unreliable and reduced the accuracy of the predictions. The space agency had ignored the forecasts NOAA published in 1976, leading some cynics to attribute self-serving motives to the forecasters at Marshall: since Huntsville still had thoughts of using *Skylab* somehow, it was not in their center's interest to acknowledge that the space station might fall to earth before it could be rescued.[7] Since no such proposals were ever formalized, the simpler explanation—that *Skylab* was simply forgotten in the press of more urgent business—is equally credible.

REGAINING CONTROL OF *SKYLAB*

Early in 1978 *Skylab* was rudely thrust into the glare of publicity—like earlier NASA activities, by the Soviet space program. The unmanned *Cosmos 954*, apparently as a result of systems failure, flamed into the atmosphere over northern Canada, scattering pieces of its nuclear-fueled electrical power module over a wide area. The module contained 45 kilograms of uranium highly enriched in the fissionable uranium-235 isotope, and an intensive search for the pieces was started immediately.[8]

Coming so soon after the arguments of the previous month, the *Cosmos* reentry produced immediate concern for what might happen when *Skylab* came down. NASA's public affairs office assured the world that the cluster contained no radioactive material and that it would not drop below 278 kilometers before October 1979.[9] That was hardly reassuring, since it cut nearly four years from previous estimates of *Skylab*'s life expectancy.

As far as NASA was concerned the most stimulating reaction was a query from the State Department. In view of worldwide interest in *Cosmos*, State wanted to know, what did NASA propose to do about *Skylab*?[10] Diplomatic repercussions were possible almost anywhere in the world if a piece of *Skylab* fell on a citizen somewhere, since the laboratory's orbital path took it over the heads of 90% of the world's population. Although NASA's studies had shown that the risk to humans was small, it was not zero—a fact that was important to any agency sensitive to public opinion in the late 1970s.

NASA immediately got to work to determine the condition of *Sky-*

lab's systems. If the derelict were to be reboosted for later use or brought out of orbit at a site of NASA's choosing, it was necessary to determine how much control could be exercised from the ground. In the most favorable circumstances this was limited to controlling the cluster's attitude, thereby decreasing or increasing atmospheric drag; it was impossible to increase its altitude. If everything worked well *Skylab*'s orbital lifetime might be extended by as much as five months, which might—just might—give Shuttle engineers enough time to get the reboost mission aloft. Toward the end of February, an eight-man team—four from Marshall and four from JSC—went to Kindley Naval Air Station, Bermuda, the only tracking station that could still transmit the UHF signals that operated the obsolete telemetry equipment aboard *Skylab*.[11]

Meanwhile, during NASA's budget hearings, Administrator Robert Frosch explained to the Senate space committee what the agency was trying to do and the difficulties it was encountering. He was still hopeful that the teleoperator retrieval system could be built in time for launch in October 1979, but by his own estimates the odds were only 50–50 that *Skylab* would still be in orbit by then. Frosch pointed out that the projections were based on forecasts of sunspot activity and were therefore much less accurate than he would prefer. William C. Schneider explained to the senators what the reboost mission involved. The 4540-kilogram teleoperator unit, mostly fuel tanks and engines, would be guided by an astronaut in the Shuttle orbiter to dock at the multiple docking adapter, whereupon its thirty-two 100-newton thrusters would push the workshop into a higher orbit. Design studies were already under way. Fabrication and assembly were scheduled to begin in six months, and the completed module was to be delivered to the Cape in early September 1979 for an October launch on the third orbiter test flight.[12] It was an ambitious schedule, considering that the first orbiter had not yet been launched.

The engineers in Bermuda made their first contact with *Skylab* the following month. Working with the North American Air Defense Command (NORAD), they located the workshop by radar, aimed a radio signal at it, and received a response. For two minutes *Skylab* reported on the condition of its systems, then fell silent. Apparently it was rotating at about 10 revolutions per hour, and when its solar panels turned out of the sunlight the radio transmissions ceased. The first thing the engineers needed to do was to charge the batteries, and since they could transmit commands only briefly once during each orbital pass, this would take time. Within a week, however, they had charged two batteries, determined the workshop's attitude, and ascertained that the onboard computer could be used to help control the spacecraft.[13]

The next goal was to gain control of the workshop systems, principally the control moment gyros, the thruster attitude control system, and the attitude-sensing rate gyros. Once these were in hand, flight controllers could keep the workshop in a minimum-drag attitude, conserving altitude until the fate of the Shuttle mission was clear. After that they could either maintain the low-drag profile or increase the drag, which would give them some control over the point of impact when the workshop finally reached the end of the road. Since all these operations required power, the solar panels had to be kept in sunlight as much as possible. Balancing these requirements was a complex job that could not be handled by a skeleton crew at a remote site, so in June a control center was jury-rigged at Johnson Space Center and manned by two teams of flight controllers. Shortly thereafter the station at Madrid was brought into the tracking network; later, Goldstone in California and a station near Santiago, Chile, would be added.[14]

By early June the JSC team had turned on the two functioning control moment gyros and used them to stabilize the cluster in a low-drag attitude that allowed them to keep the batteries charged. This was not accomplished with great ease, for the gyro that had given Houston so much worry during the last days of the third mission again showed signs of stress—decreased wheel speed and increased motor currents. Besides that, the refrigerating systems that cooled the batteries in the airlock module were ailing; one had lost nearly all its cooling fluid, and the other was not completely reliable. Juggling the demands of power production and minimum drag with these complications thrown in took a great deal of planning, and crews worked 10-hour shifts through the summer. In July they almost had to start all over again when a spurious telemetry signal caused the computer to switch the control moment gyros off and the gas thrusters on; a significant fraction of the remaining propellant was used before the Houston team could regain control.[15]

Meanwhile Headquarters was setting up an organization to deal with the problems that would arise when *Skylab* came back to earth. On 25 July a Skylab Contingency Working Group was established to coordinate interagency planning. Under the direction of William G. Bastedo, this group was responsible for a host of activities, from keeping track of *Skylab*'s condition to informing foreign governments of the current state of affairs. Besides NASA participants, the group included members from the departments of State, Justice, and Defense.[16]

The effort to save *Skylab* was becoming costly. Not counting expenditures for hardware development, NASA had spent $750 000 on the dying workshop by 1 June 1978 and expected to lay out at least $3 million more by the end of the year. At least one official thought this money was largely wasted. Chris Kraft, director of JSC, publicly expressed his opinion that the effort was futile. He did not expect the *Skylab* systems to continue functioning long enough for its reentry to be controlled (tacitly implying that there was no hope for the reboost mission). He conceded that his engineers were obliged to do everything they could, but thought that NASA would not have gone to such lengths if the *Cosmos* accident had not focused so much attention on falling spacecraft fragments—attention that Kraft evidently felt *Skylab* did not deserve. In his opinion the money would have been far better spent on the Shuttle program, which was falling behind schedule for lack of adequate funding. In Washington, however, where the White House and the State Department could look over his shoulder, Robert Frosch reiterated the agency's determination to continue the effort in spite of the very small chance that *Skylab* would hit anyone.[17]

As summer turned to fall the Houston operation, directed by Charles Harlan of JSC's Flight Control Division, began working around the clock. Addition of the tracking station in Chile gave complete coverage throughout each of *Skylab*'s revolutions, and by October 1978 Harlan had enough people to set up five flight control teams that worked three shifts a day. A few had sat behind control consoles during the Skylab manned missions, but most were new.[18]

The Skylab working group had a rehearsal of sorts in September, when the unmanned satellite *Pegasus 1* came out of orbit.* The exercise served mainly to evaluate impact prediction models, using orbital data from NORAD, as well as to establish interagency procedures. Having checked out its communications and models, the group monitored *Pegasus*'s uneventful reentry over the southwestern African coast on 17 September. From this exercise, goals were set for the eventual demise of *Skylab*.[19]

Having started with little confidence in the aging systems on board the orbital cluster, but having discovered that those systems were better built than they expected, flight controllers developed real enthusiasm for their task. The problem was important enough to be worthwhile and difficult enough to be challenging. Early in the summer they had determined that they could use the onboard computer, and Marshall control-system engineers devised new programs to control the spacecraft's attitude without using the gas thrusters. The remaining fuel for these had to be kept in reserve, for they would be needed if the reboost module should reach the workshop. The batteries had to be watched constantly. As those in use heated up, others were put on line to replace them; occasionally they all warmed up and the cooling system had to be switched on long enough to return them to normal temperature. As the relation of *Skylab*'s orbital plane to the sun changed, all the variables changed.

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* *Pegasus 1* was launched 16 February 1965 as part of the payload on the test mission AS-9, which also carried a boilerplate Apollo spacecraft into orbit for tests. Two more Pegasus satellites were flown on similar missions; they carried equipment to measure and report the number and velocity of micrometeoroids at orbital altitude.

Many hours were spent devising and testing new combinations. Then in November the sick control moment gyro slowed down even more. The workshop was turned around, to expose the gyro to sunlight and warm up its bearings so that lubricant might flow more freely. The maneuver had been used during the third mission with ambiguous results, but since the gyro was now operating far outside the limits reached during the manned mission it seemed worth trying; loss of this gyro would seriously complicate the problem. In the event, both gyros lasted until reentry.[20]

LAST DAYS OF *SKYLAB*

The year-long effort to keep *Skylab* aloft ended in December 1978 Although the teleoperator propulsion module was approaching final assembly, problems with Shuttle's main engines had delayed critical tests, and program officials clearly saw that the reboost mission could not be launched by October. Frosch advised the President on 15 December that *Skylab* could not be saved but that NASA would do all it could to control reentry to minimize the risk to populated areas. John Yardley, associate administrator for the Office of Space Transportation Systems (successor to the Office of Manned Space Flight), provided details of the decision to the press on the 19th. Shuttle schedules had slipped so far that the reboost mission could not be launched before March 1980, and the workshop's rapidly decaying orbit, plus the increasing difficulty of controlling its attitude, made rescue impossible.[21]

The decision would simplify the work of Houston's flight control teams, though not immediately. For six more weeks they worked three shifts a day, holding *Skylab* in its low-drag attitude until policymakers could decide exactly how to manage the reentry. Choices were severely limited. As soon as the decision was reached, Bastedo sent a detailed reentry plan to the departments of State, Defense, and Justice and to the Federal Preparedness Agency for comment. A meeting with NORAD on 9 January 1979 established radar tracking requirements and set up formal technical liaison. Reentry information from NORAD would be transmitted to NASA field centers and to a coordination center to be set up by Yardley's office to direct the reentry.[22] The operation was only slightly less elaborate than preparations for the return of an Apollo flight.

One of the Skylab group's chief functions was to ensure that NASA spoke with a single voice during the months remaining before reentry. Since NASA and NORAD used different models to predict reentry times, it was important that public statements about the date and place of reentry be consistent. This precaution was wiser than it seemed at the time. Three months later, when a nuclear reactor accident in Pennsylvania almost required evacuation of several thousand people, much confusion resulted when different experts made conflicting public statements as to the level of danger.

Now that *Skylab* was certain to come down, television and the press looked forward to an event that might prove spectacular and in any case would be newsworthy. Much as they had done with Comet Kohoutek (app. F), reporters and headline writers began to play up the coming reentry. Some bizarre by-products of the event provided an occasional flash of weird humor. In Washington, two computer specialists established a firm called Chicken Little Associates, offering to provide up-to-the-minute estimates of the danger to any specific person, for a fee. With the implication that NASA's predictions were unreliable, Chicken Little drew publicity—especially abroad. Then, just a month before reentry, a group from the Brookline (Mass.) Psychoenergetics Institute attempted to increase *Skylab*'s altitude by telekinesis. They staged a "coordinated meditation" session in several eastern states, but produced no effect detectable on NORAD's radars.[23]

In Washington and Houston, more serious preparations continued. Bastedo's staff finished the NASA reentry plan and sent it to the White House on 30 January. March offered a second opportunity to check out refined procedures when *HEAO 1*, a NASA astronomical satellite, returned to earth. Data links between NORAD, Washington, and Huntsville were checked out. As a final rehearsal, the Skylab group, NORAD, MSFC, and JSC followed the reentry of a Soviet rocket body 27–29 April. This target of opportunity was used to determine the state of readiness of all participants in the *Skylab* reentry. In June, a paper simulation was run as a last check.[24]

Work at the control center at JSC had slacked off somewhat in early February, following a decision to return the workshop to solar-inertial attitude. Since power management was much easier in this attitude, round-the-clock monitoring of systems was suspended for several weeks and many of the flight control people were sent back to their regular jobs. Attitude control too was comparatively easy in solar inertial, in spite of the increased drag, but it was expected to become more difficult as the workshop lost altitude. From February through May, however, the control center simply kept an eye on *Skylab* while plans were made for its last few orbits.[25]

Toward the end of April, Headquarters issued its first forecast of a reentry date calculated from NORAD's model. On the 25th, when the workshop had fallen to about 320 kilometers, NORAD estimated a probability of 50% that *Skylab* would come down by 19 June; there was a 90% chance that it would reenter between 13 June and 1 July. This format was used consistently for the rest of the waiting period, because it was impossible to give a more precise estimate until reentry had virtually begun. Marshall's engineers used a slightly different forecasting model; they estimated reentry between 15 and 22 June, but their estimates were never publicized. NORAD was in the business of tracking satellites and NASA used NORAD's forecasts for public utterances.[26]

Since flight controllers were not vitally interested in NORAD's predictions, the discrepancy was not particularly bothersome. The two groups did exchange information, however, and determined the different ways the two computer models treated data. NORAD made a fairly straightforward extrapolation based on recent observations, while NASA continuously took account of changing atmospheric density and the spacecraft's drag profile as it came down. Harlan reasoned that the two predictions would converge rapidly as reentry approached, which turned out to be the case.[27]

By the end of May, engineers and managers had agreed on a method of controlling the reentry. *Skylab* would be placed in a high-drag "torque equilibrium" attitude, in which aerodynamic forces were balanced by the control moment gyros as long as they had the capability. This would subject the workshop to a known retarding force from which impact predictions could be made. Flight controllers could then reduce drag if necessary to shift the reentry point. When the cluster fell to 140 kilometers, it would be set to tumbling end-over-end, reducing the drag to a known level and allowing a reasonably accurate prediction of impact. Theoretically impact could be shifted by as much as five orbits by changing the tumbling altitude, but that would tax the systems to their limit. A shift of one to three orbits was a more realistic expectation. The torque-equilibrium attitude made power management more complex, so the Houston center went back to 24-hour surveillance and control.[28]

Meanwhile each ground track covered by *Skylab* was assigned a "hazard index," ranging from 0 to 100, depending on the population exposed on that track compared with the least dangerous track. On the basis of these numbers Harlan might have to shift the impact point to an orbit of lower risk in the last hours of flight. It was a statistical game—sensible, but offering no assurance of safety. As Harlan commented later, "Clearly you could come in on an orbit with a lot of people and not hit a soul, or you could come in on an orbit with a few people and hit a schoolhouse and kill a bunch of kids." Administrator Frosch's testimony before a House subcommittee in June pointed up NASA's predicament. He reiterated the small risk of human injury (1 chance in 152), and emphasized that the fragments would be widely scattered. Although Frosch could not give absolute assurance that no one would be injured, he tried his best to convince his audience that there was really not much to worry about.[29]

Statistical arguments, however, are inherently unconvincing, at least to the general public; and Frosch's assurances were the less comforting because a few of the fragments might weigh several hundred kilograms when they reached the surface. It was clear that the decision made in 1970 was definitely embarrassing nine years later. The space agency was feeling the effects of a change in public attitude toward technology generally and space technology in particular. A large fraction of the public was unwilling to accept *any* risk from a high-technology program, especially when the average citizen could do nothing to protect himself from that risk. Congressmen and editors demanded to know why *Skylab* had been launched without the means of controlling its reentry, and Frosch could only answer that it had seemed too expensive at the time.

The workshop was down to 261 kilometers on the 20th of June, having fallen 60 kilometers in the previous four weeks. During June NORAD issued predictions periodically; the median date (by which time there was an even chance that the workshop would have come to earth) moved from 16 July to 12 July, while the spread narrowed: 7–25 July predicted on 14 June, 10–18 July on the 28th.[30]

As reentry approached, the difference between NORAD's predictions and NASA's caused some small problems. Television networks, needing time to prepare for coverage of the event, called Houston to ask when they should send reporting teams. Harlan and the JSC Public Affairs Office felt obliged to give them a date in which they themselves had some confidence, so they told the media officials to come a day or two before the official predictions called for reentry. This could have caused some embarrassment for Headquarters, but nobody publicized the point.[31]

Early in July the end was approaching rapidly. The workshop became harder to control as it dropped into the denser atmosphere, and power supplies were increasingly difficult to manage. On 9 July 1979 the Skylab Coordination Center opened in NASA Headquarters. With direct telephone lines to NORAD, NASA field centers, the State and Defense departments, and the FAA, the center was capable of relaying information and orders almost instantly. A closed-circuit TV display from Houston pictured *Skylab*'s ground track for several orbits, as well as the current position. Newsmen and other nonessential personnel were kept out of the operations room itself, but the closed-circuit TV, tracking charts, and periodic briefings kept the crowd in the larger newsroom informed. On opening day the center issued the prediction that *Skylab* would come down on 11 July between 2:10 a.m. and 10:10 p.m. EDT, most probably on its 34 981st orbit. It was then at an altitude of 190 kilometers. The following day it dropped 17 km and the reentry time was bracketed between 7:02 a.m. and 5:02 p.m. EDT on the 11th.[32]

In Houston, Charles Harlan and his team stood by to make their last decision. For some hours before reentry the computers gave the same prediction: the workshop was coming down on 11 July. The only question that remained was the timing of the final tumbling maneuver. During the last hours of 10 July it appeared that *Skylab* would reenter on the best possible orbit of the day on the 11th, an orbit passing across southern Canada and the east coast of the United States and then over a long stretch of open ocean to Australia, the next landfall. But early calculations of the debris pattern showed that if tumbling were initiated at 140 kilometers as planned, the western end of the 7400 × 185 km "footprint" would slightly overlap North America. JSC officials then recommended, and Headquarters concurred, that the cluster be tumbled sooner, to move the predicted impact area downrange. Harlan picked an area about 1300 kilometers south-southeast of Cape Town, South Africa, halfway between North America and Australia and south of the shipping lanes, which would require tumbling at 148 kilometers. The command was executed at 3:45 a.m. EDT, and the workshop went into an end-over-end spin.[33]

Skylab had one more trick up its sleeve, however—one that gave flight controllers some anxious moments on the last orbit. They expected the cluster to come apart before it passed over the east coast of the U.S., but radar operators at Bermuda reported only a single image. Over Ascension Island the workshop still had not broken up; a NORAD imaging radar clearly showed that even the fragile solar arrays were still intact. But the telemetry was faltering and stopped entirely as the craft passed south of Africa. Its unexpected tenacity had shifted the impact ellipse considerably to the east, however, and there was a possibility that Australia would catch some of the heavy fragments, which would fall at the eastern end of the ellipse.[34]

NORAD computed that impact occurred at 12:37 p.m. EDT. Shortly before 1 p.m., the Washington control center received word that the area southeast of Perth, Australia, had indeed been showered with pieces. Spectacular visual effects were reported and many residents heard sonic booms and whirring noises as the chunks passed overhead in the early morning darkness. Officials waited anxiously for news of injury or property damage, but none came. *Skylab* was finally down and NASA had managed it without hurting anyone.[35]

One Australian, in fact, profited handsomely from the overshoot. A San Francisco newspaper had offered $10 000 for the first authenticated piece of *Skylab* brought to its office within 48 hours of reentry, and on the morning of 13 July a claimant appeared. Stan Thornton, a 17-year-old beer-truck driver from the small coastal community of Esperance, had found some charred objects in his back yard, bagged them up, and caught the first plane for California. He arrived without passport and with only a shaving kit for luggage, but the pieces were identified as remains of plastic or wood insulation from *Skylab*, and Thornton got his prize.[36]

Examining their data after reentry, Harlan and his team decided that they had miscalculated drag during tumbling. It was a small relative error—only 4%—but it had shifted the impact zone hundreds of kilometers farther east than they had wanted. Fortunately the reentry orbit passed over the sparsely settled ranch country of Western Australia, but it was a slightly inelegant end to an otherwise well managed reentry.[37]

Little remained to be done. The makeshift control centers at Headquarters, JSC, and MSFC were dismantled; Harlan and his co-workers went back to their jobs grappling with Shuttle's problems. Five Marshall engineers went to Australia to test the fragments that had been recovered, search for others, and try to establish the actual pattern. Some indignation had been expressed by Australian newspapers just after the reentry, but the NASA team was greeted warmly and given all possible assistance in their mission. Some pieces of the workshop had been put on display in Coolgardie and other nearby towns, but a cursory search found no others. Doubtless many remained scattered across the dusty ranches of the outback, to be stumbled upon some day by a herder or fence rider.[38]

Meanwhile, just three days after *Skylab*'s reentry, two Soviet cosmonauts aboard *Salyut 6* established a new record for endurance in earth orbit. The record they broke was not *Skylab*'s but one that had been set only the year before by another Soviet crew.[39]

Appendixes

A. Summary of the Missions
B. Major Contractors
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Appendix A
Summary of the Missions

	Skylab 1 (orbital cluster)	Skylab 2 (1st crew)	Skylab 3 (2d crew)	Skylab 4 (3d crew)	Totals
Launch	14 May 1973 1:30 p.m. EDT	25 May 1973 9:00 a.m. EDT	28 July 1973 7:11 a.m. EDT	16 Nov. 1973 9:01 a.m. EST	
Return	11 July 1979 12:37 p.m. EDT	22 June 1973 9:49 a.m. EDT	25 Sept. 1973 6:19 p.m. EDT	8 Feb. 1974 11:17 a.m. EDT	
Vehicles	Saturn V SA-513 (2 stages)	Saturn IB SA-206, CSM-116	Saturn IB SA-207, CSM-117	Saturn IB SA-208, CSM-118	
Orbital inclination	50°				
Orbital parameters (km)	431.5 × 433.7				
Orbital period	93 min approx.				
Mission duration		28 days 49 min	59 days 11 hr 9 min	84 days 1 hr 14 min	171 days 13 hr 12 min
Number of revolutions (manned)		404	858	1214	2476
Distance traveled (km, manned)		18 500 000	39 400 000	55 500 000	113 400 000
Crews					
Commander		Capt. Charles Conrad, Jr., USN	Capt. Alan L. Bean, USN	Lt. Col. Gerald P. Carr, USMC	

Scientist-Pilot	Cmdr. Joseph P. Kerwin, MC, USN		Owen K. Garriott, Ph.D.		Edward G. Gibson, Ph.D.			
Pilot	Cmdr. Paul J. Weitz, USN		Maj. Jack R. Lousma, USMC		Lt. Col. William R. Pogue, USAF			
Manhour Utilization	Hours	%	Hours	%	Hours	%	Hours	%
Sleep, rest, off duty	675.6	34.9	1224.5	31.2	1846.5	30.5	3746.6	31.4
Experiments	392.2	20.2	1081.5	27.6	1563.2	25.8	3036.9	25.6
Presleep, postsleep meals	477.1	24.7	975.7	24.9	1384.0	23.0	2836.8	23.8
Physical training, hygiene	56.2	2.9	202.2	5.2	384.5	6.4	642.9	5.4
Housekeeping	103.6	5.3	158.4	4.0	298.9	4.9	560.9	4.7
Other	232.5	12.0	279.7	7.1	571.4	9.4	1083.6	9.1
Totals	1937.2		3922.0		6048.5		11907.7	
Experiment Performance	Hours	%	Hours	%	Hours	%	Hours	%
Solar astronomy	117.2	29.9	305.1	28.2	519.0	33.2	941.3	31.0
Life science	145.3	37.0	312.5	28.9	366.7	23.5	824.5	27.1
Earth resources	71.4	18.2	223.5	20.7	274.5	17.6	569.4	18.8
Astrophysics	36.6	9.4	103.8	9.6	133.8	8.6	274.2	9.0
Engineering & technology	12.1	3.1	117.4	10.9	83.0	5.3	212.5	7.0
Comet Kohoutek					156.0	10.0	156.0	5.1
Materials science	5.9	1.5	8.4	0.8	15.4	1.0	29.7	1.0
Student experiments	3.7	0.9	10.8	1.0	14.8	0.9	29.3	1.0
Totals	392.2		1081.5		1563.2		3036.9	
Data Returned								
Solar astronomy, frames	28 739		24 942		73 366		127 047	
Earth resources, frames	9 846		16 800		19 400		46 046	
Earth resources, meters of tape	13 716		28 529		30 480		72 725	

	Skylab 1 (orbital cluster)	Skylab 2 (1st crew)	Skylab 3 (2d crew)	Skylab 4 (3d crew)	Totals
Extravehicular Activity		Standup 25 May 73 37 min	EVA 1, 6 Aug 73 6 hr 29 min	EVA 1, 22 Nov 73 6 hr 33 min	
		EVA 1, 7 Jun 73 3 hr 30 min	EVA 2, 24 Aug 73 4 hr 30 min	EVA 2, 25 Dec 73 7 hr 1 min	
		EVA 2, 19 Jun 73 1 hr 44 min	EVA 3, 22 Sep 73 2 hr 45 min	EVA 3, 29 Dec 73 3 hr 28 min	
				EVA 4, 8 Feb 74 5 hr 19 min	
Totals		5 hr 51 min	13 hr 44 min	22 hr 21 min	41 hr 56 min

SOURCE: *MSFC Skylab Mission Report—Saturn Workshop* (NASA TM X-64814, Oct. 1974), p. 3-39; Roland W. Newkirk and Ivan D. Ertel, with Courtney G. Brooks, *Skylab: A Chronology* (NASA SP-4011, 1977), pp. 362–64.

Appendix B
Major Contractors

Contractor	Responsible Center	Contract	
		Task	Amount (millions)
McDonnell Douglas Astronautics	MSFC	Orbital workshop	$383.3
Rockwell International	JSC	Command and service modules	354.3
McDonnell Douglas Astronautics	MSFC	Airlock module	267.7
Martin Marietta	MSFC	Payload integration and multiple docking adapter assembly	215.5
Martin Marietta	JSC	Payload and experiments integration and spacecraft support	105.4
McDonnell Douglas Astronautics	KSC	S-IVB launch services	58.9
Naval Research Laboratory	MSFC	S082A, B, ultraviolet spectroheliograph and spectrograph	40.9
Harvard College Observatory	MSFC	S055 ultraviolet spectrometer	34.6
International Business Machines	MSFC	Instrument unit	30.7
Chrysler	MSFC	S-IB stage	30.0
General Electric	JSC	Reliability and quality assurance systems engineering for auto. checkout equipment	29.7
International Business Machines	MSFC	Apollo telescope mount digital computer	29.2
McDonnell Douglas Astronautics	MSFC	S-IVB stage	25.7
General Electric	MSFC	Electrical support equipment, logistic support	25.0
Chrysler	KSC	S-IB launch operations support	23.2
Rockwell International	KSC	Command and service module support	17.5
International Latex Corp.	JSC	Spacesuits	16.9
High Altitude Observatory	MSFC	S052 white light coronagraph	14.7
Boeing	KSC	Saturn V vehicle and launch operations support	14.4
General Electric	MSFC	Launch vehicle ground support equipment	12.6

Contractor	Responsible Center	Contract	
		Task	Amount (millions)
International Business Machines	KSC	Instrument unit launch services	12.3
Garrett	JSC	Portable astronaut life support assembly	11.9
General Electric	JSC	S193 microwave radiometer-scatterometer	11.3
Martin Marietta	Hqs.	Program support	11.1
Honeywell	JSC	S192 10-band multispectral scanner	10.8
Rockwell International	MSFC	Saturn engine support, Saturn V and IB	10.3
American Science & Engineering	MSFC	S054 x-ray spectrographic telescope	8.3
Boeing	MSFC	Systems engineering and integration	7.4
Martin Marietta	KSC	Multiple docking adapter support	7.2
Chrysler	MSFC	S-IB systems and integration	7.0
Itek	JSC	S190 multispectral photographic facility	2.7
Goddard Space Flight Center	MSFC	S056 dual x-ray telescope	2.5
Block Engineering	JSC	S191 infrared spectrometer	2.0
Cutler Hammer Airborne Instruments	JSC	S194 L-band radiometer	1.5
Boeing	MSFC	S-IC stage	0.9
Delco Electronics	KSC	Navigation and guidance launch operations	0.9

SOURCE: Senate Committee on Aeronautical and Space Sciences, *Skylab: Status of Skylab Mission*, hearing, 93d Congress, 1st sess., 23 May 1973, p. 25.

Appendix C
International Aeronautical Federation World Records Set by Skylab

Mission	Crew	Category	Performance
Skylab 2 (1st crew)	Charles Conrad, Jr. Joseph P. Kerwin Paul J. Weitz	Absolute duration of flight	28 days 0 hr 49 min 49 sec
		Absolute distance traveled	18 536 730.9 km
		Accumulated spaceflight time for one astronaut (Conrad)	49 days 3 hr 38 min 36 sec
		Duration in earth orbit	28 days 0 hr 49 min 49 sec
		Duration in linked configuration	27 days 6 hr 48 min 7 sec
		Distance traveled in earth orbit	18 536 730.9 km
		Distance traveled in linked configuration	18 059 390.9 km
		Total time in space for orbital mission for one astronaut (Conrad)	38 days 23 hr 2 min 11 sec
		Greatest mass linked	88 054.5 kg
Skylab 3 (2d crew)	Alan L. Bean Owen K. Garriott Jack R. Lousma	Absolute duration of flight	59 days 11 hr 9 min 4 sec
		Absolute distance traveled	39 309 605.6 km
		Accumulated spaceflight time for one astronaut (Bean)	69 days 15 hr 45 min 29 sec
		Duration in earth orbit	59 days 11 hr 9 min 4 sec
		Duration in linked configuration	59 days 0 hr 9 min 42 sec
		Distance traveled in earth orbit	39 309 605.6 km
		Distance traveled in linked configuration	39 007 368.4 km
		Total time in earth orbit for one astronaut	59 days 11 hr 9 min 4 sec

Mission	Crew	Category	Performance
Skylab 4 (3d crew)	Gerald P. Carr William R. Pogue Edward G. Gibson	Absolute duration of flight	84 days 1 hr 15 min 30 sec
		Absolute distance traveled	55 474 039.4 km
		Accumulated spaceflight time for one astronaut	84 days 1 hr 15 min 30 sec
		Duration in earth orbit	84 days 1 hr 15 min 30 sec
		Duration in linked configuration	83 days 12 hr 32 min 12 sec
		Distance traveled in earth orbit	55 474 039.4 km
		Distance traveled in linked configuration	55 127 746.9 km
		Total time in earth orbit for one astronaut	84 days 1 hr 15 min 30 sec

SOURCE: Carl R. Huss, Data Systems and Analysis Directorate, Johnson Space Center.

Appendix D
Experiments

Number	Title	Location in Skylab	Principal Investigators	Crew 1	Crew 2	Crew 3
	SOLAR STUDIES					
S020	Ultraviolet and x-ray solar photography[1]	OWS/SAL	R. Tousey, U.S. Naval Research Laboratory		X	X
S052	White-light coronagraph	ATM	R. MacQueen, High Altitude Observatory	X	X	X
S054	X-ray spectrographic telescope	ATM	R. Giacconi, G. Vaiana, American Science and Engineering Corp.	X	X	X
S055	Ultraviolet scanning spectroheliometer	ATM	L. Goldberg, E. M. Reeves, Harvard College Observatory	X	X	X
S056	X-ray telescope	ATM	J. E. Milligan, MSFC	X	X	X
S082A	Extreme ultraviolet spectroheliograph	ATM	R. Tousey	X	X	X
S082B	Ultraviolet spectrograph	ATM	R. Tousey	X	X	X
	STELLAR ASTRONOMY					
S019	Ultraviolet stellar astronomy	OWS/SAL	K. G. Henize, JSC	X	X	
S150	Galactic x-ray mapping[2]	IU	W. L. Kraushaar, Univ. of Wisconsin			X
S183	Ultraviolet panorama telescope	OWS/SAL	G. Courtès, Laboratoire d'Astronomie Spatiale, France	X	X	
	SPACE PHYSICS					
S009	Nuclear emulsion package	MDA	M. M. Shapiro, Naval Research Lab.	X		
S063	Ultraviolet airglow horizon photography	OWS/SAL	D. M. Packer, Naval Research Lab.	X		
S073	Gegenschein and zodiacal light	OWS/SAL	J. J. Weinberg, Dudley Observatory	X	X	X

Number	Title	Location in Skylab	Principal Investigators	Crew		
				1	2	3
S149	Micrometeoroid particle collection[3]	OWS/EVA	C. L. Hemenway, Dudley Observatory	X	X	X
S228	Transuranic cosmic rays	OWS/EVA	P. B. Price, U. California Berkeley	X	X	X
S230	Magnetospheric particle composition	ATM/EVA	D. L. Lind, JSC, and Johannes Geiss, Univ. of Berne, Switzerland	X	X	X
	EARTH RESOURCES EXPERIMENTS					
S190A	Multispectral photographic cameras	MDA	Project scientist: K. Demel, JSC	X	X	X
S190B	Earth terrain camera	OWS/SAL	Project scientist: K. Demel, JSC	X	X	X
S191	Infrared spectrometer	MDA	T. L. Barnett, JSC	X	X	X
S192	Multispectral scanner	MDA	C. K. Korb, JSC	X	X	X
S193	Microwave radiometer/scatterometer and altimeter[4]	MDA	E. Evans, JSC	X	X	X
S194	L-band radiometer	MDA	E. Evans, JSC	X	X	X
	LIFE SCIENCES PROJECTS					
M071	Mineral balance	OWS	G. D. Whedon, Natl. Institutes of Health, and L. Lutwak, Cornell Univ.	X	X	X
M073	Bioassay of body fluids	OWS	C. S. Leach, JSC	X	X	X
M074	Specimen mass measurement	OWS	W. E. Thornton, JSC, and J. W. Ord, Clark Air Force Base	X	X	X
M078	Bone mineral measurement	—	J. M. Vogel, U.S. Public Health Service Hospital, San Francisco, and J. R. Cameron, U. Wisconsin Med. Center		[14]	
M092	Lower-body negative-pressure device	OWS	R. L. Johnson, JSC, and J. W. Ord, Clark AFB	X	X	X
M093	Vectorcardiogram	OWS	N. W. Allenbach, U.S. Naval Aerospace Med. Inst., and R. F. Smith, Vanderbilt Univ. Med. School	X	X	X
M111	Cytogenetic studies of blood	—	L. H. Lockhart, U. Tex. Med. Br., and P. C. Gooch, Brown & Root-Northrop		[14]	

Number	Title	Location in Skylab	Principal Investigators	Crew 1	Crew 2	Crew 3
M112	Man's immunity, in-vitro aspects	OWS	S. E. Ritzmann and W. C. Levin, U. Tex. Med. Br.	X	X	X
M113	Blood volume and red cell life span	OWS	P. C. Johnson, Baylor U. Med. School	X	X	X
M114	Red blood-cell metabolism	OWS	C. E. Mengel, U. Missouri Sch. of Med.	X	X	X
M115	Special hematological effects	OWS	S. L. Kimsey and C. L. Fischer, JSC	X	X	X
M131	Human vestibular function	OWS	A. Graybiel and E. F. Miller, Navy Aerospace Med. Institute	X	X	
M133	Sleep monitoring	OWS	J. D. Frost, Jr., Baylor U. Coll. of Med.	X	X	
M151	Time and motion study	OWS	J. F. Kubis, Fordham U., and E. J. McLaughlin, NASA Hq.	X	X	X
M171	Metabolic activity	OWS	E. L. Michel and J. A. Rummel, JSC	X	X	X
M172	Body mass measurement	OWS	W. E. Thornton, JSC	X	X	X
S015	Effect of zero gravity on single human cells	CM	P. O. Montgomery and J. Paul, U. of Tex. Southwestern Med. School	X		
S071	Circadian rhythm, pocket mice[5]	CSM	R. G. Lindberg, Northrop Corp. Labs.		X	
S072	Circadian rhythm, vinegar gnats[5]	CSM	C. S. Pittendrigh, Stanford Univ.		X	
	MATERIAL SCIENCE & MANUFACTURING IN SPACE					
M479	Zero-gravity flammability	MDA	J. H. Kimzey, JSC			X
M512	Materials processing facility[6]	MDA	P. G. Parks, MSFC	X		X
(M551)	Metals melting	MDA	R. M. Poorman, MSFC	X		
(M552)	Exothermic brazing	MDA	J. Williams, MSFC	X		
(M553)	Sphere forming	MDA	E. A. Hasemeyer, MSFC	X		
(M555)	Gallium arsenide crystal growth	MDA	M. Rubenstein, Westinghouse Electric Corp.	X		
M518	Multipurpose electric furnace system[7]	MDA	A. Boese, MSFC, project engineer			X
(M556)	Vapor growth of II-VI compounds	MDA	H. Wiedemeir, Rensselaer Polytechnic Inst.			X
(M557)	Immiscible alloy compositions	MDA	J. Reger, TRW			X
(M558)	Radioactive tracer diffusion	MDA	T. Ukanwa, MSFC			X
(M559)	Microsegregation in germanium	MDA	F. Padovani, Texas Instruments			X
(M560)	Growth of spherical crystals	MDA	H. Walter, Univ. Alabama at Huntsville			X

Number	Title	Location in Skylab	Principal Investigators	Crew 1	Crew 2	Crew 3
(M561)	Whisker-reinforced composites	MDA	T. Kawada, Natl. Research Inst. for Metals, Japan			X
(M562)	Indium antimonide crystals	MDA	H. Gatos, Mass. Inst. of Technology			X
(M563)	Mixed III-V crystal growth	MDA	W. Wilcox, Univ. of Southern California			X
(M564)	Halide eutectics	MDA	A. Yue, Univ. of Calif. at Los Angeles			X
(M565)	Silver grids melted in space	MDA	A. Deruythere, Catholic Univ. of Leuven, Belgium			X
(M566)	Copper-aluminum eutectic	MDA	E. Hasemeyer, MSFC			X
	ZERO-GRAVITY SYSTEMS STUDIES					
M487	Habitability-Crew Quarters	OWS	C. C. Johnson, MSC	X	X	X
M509	Astronaut maneuvering equipment	OWS	C. E. Whitsett, Jr., USAF Space & Missile Systems Org.		X	X
M516	Crew activities and maintenance study	OWS	R. L. Bond, JSC	X	X	X
T002	Manual navigation sightings	OWS	R. J. Randle, Ames Research Center		X	X
T013	Crew vehicle disturbances	OWS	B. A. Conway, Langley Research Center		X	
T020	Foot-controlled maneuvering unit	OWS	D. E. Hewes, Langley Research Center		X	X
	SPACECRAFT ENVIRONMENT					
D008	Radiation in spacecraft	CM	A. D. Grim, Kirtland Air Force Base	X		
D024	Thermal control coatings	AM	W. Lehn, Wright-Patterson Air Force Base	X		
M415	Thermal control coatings	IU	E. C. McKannan, MSFC	X		
T003	Inflight aerosol analysis	OWS	W. Z. Leavitt, Dept. of Transportation	X	X	X
T025	Coronagraph contamination measurements	OWS	M. Greenberg, Dudley Observatory	X	X	X
T027	ATM contamination measurements	OWS	J. A. Muscari, Martin Marietta Corp.	X	X	X
	SKYLAB STUDENT PROJECT		SECONDARY SCHOOL STUDENT WINNERS			
ED11	Absorption of radiant heat in the earth's atmosphere	none[a]	J. B. Zmolek, Oshkosh, Wis.	X	X	X

Number	Title	Location in Skylab	Principal Investigators	Crew 1	Crew 2	Crew 3
ED12	Space observation and prediction of volcanic eruptions	none	T. A. Crites, Kent, Wash.	X	X	X
ED21	Photography of libration clouds	none	A. Hopfield, Princeton, N.J.		X	
ED22	Possible confirmation of objects within Mercury's orbit	none	D. C. Bochsler, Silverton, Ore.	X	X	X
ED23	Spectrography of selected quasars	none	J. C. Hamilton, Alea, Hawaii	X		
ED24	X-ray content in association with stellar spectral classes[9]	none	J. W. Reihs, Baton Rouge, La.			X
ED25	X-ray emission from the planet Jupiter[10]	none	J. L. Leventhal, Berkeley, Cal.		X	
ED26	A search for pulsars in ultraviolet wavelengths	none	N. W. Shannon, Atlanta, Ga.	X		
ED31	Behavior of bacteria and bacterial spores in the Skylab space environment	OWS	R. L. Staehle, Rochester, N.Y.	X		
ED32	An in-vitro study of selected isolated immune phenomena	OWS	T. A. Meister, Jackson Heights, N.Y.		X	
ED41	A quantitative measure of motor sensory performance during prolonged flight in zero gravity	OWS	K. L. Jackson, Houston, Tex.			X
ED52	Web formation in zero gravity	OWS	J. S. Miles, Lexington, Mass.		X	
ED61	Plant growth in zero gravity	OWS	J. G. Wordekemper, West Point, Neb.			X
ED62	Phototropic orientation of an embryo plant in zero gravity	OWS	D. W. Schlack, Downey, Cal.			X
ED63	Cytoplasmic streaming in zero gravity[11]	OWS	C. A. Peltz, Littleton, Colo.		X	
ED72	Capillary action studies in a state of free fall[12]	OWS	R. G. Johnson, St. Paul, Minn.			X
ED74	Zero gravity mass measurement	OWS	V. W. Converse, Rockford, Ill.		X	
ED76	Earth orbital neutron analysis	OWS	T. C. Quist, San Antonio, Tex.	X	X	X
ED78	Wave motion through a liquid in zero gravity[13]	OWS	W. B. Dunlap, Youngstown, Ohio			X

ABBREVIATIONS:
AM, airlock module
ATM, Apollo telescope mount
EVA, extravehicular activity
IU, instrument unit
MDA, multiple docking adapter
OWS, orbital workshop
SAL, scientific airlock

NOTES

1. Could not be operated as planned because the solar airlock was blocked by the parasol sunshade. Operated EVA by 3d crew.
2. Component failure caused instrument to shut off after operating 110 of a planned 265 minutes.
3. Deployed through antisolar airlock and left between first and second manned missions.
4. Fore-and-aft scanning failed. After repair by 3d crew, fault was locked out and cross-track scanning restored, recovering 80% of data.
5. Short circuit in equipment prevented acquisition of telemetered data.
6. M512 was a multipurpose vacuum chamber with an electron beam generator, used for conducting the experiments that follow in the list.
7. M518 was an electric furnace attaching to M512, used in performing the experiments that follow in the list.
8. No special equipment required; experiment used data from other Skylab sensors.
9. Skylab's x-ray detectors were not sufficiently sensitive to collect the data this experiment required.
10. Could not be performed. When Jupiter was in the best viewing position, the power crisis did not allow maneuvering to point at the target. An alternative target was below the detection limit of Skylab sensors.
11. Only partially completed; the water plants used in the experiment did not live long enough to make the planned observations. One successful observation was made.
12. Leakage of fluids from the experiment hardware led to inconclusive results.
13. Hardware failure negated this experiment.
14. Accomplished before and after flight with all crews.

SOURCE: Leland F. Belew and Ernst Stuhlinger, *Skylab: A Guidebook* (NASA EP-107, 1972), chap. 5.

Appendix E
Astronauts' Biographies

1st Crew

Commander: Capt. Charles Conrad, Jr., USN. Born 2 June 1930 in Philadelphia. B.S. in aeronautical engineering, Princeton University, 1953. Completed U.S. Navy Test Pilot School at Patuxent River, Md.; joined NASA in 1962 with the second group of astronauts. Pilot of *Gemini 5,* 21–29 Aug. 1965; commander of *Gemini 11,* 12–15 Sept. 1966; commander of *Apollo 12,* 14–24 Nov. 1969. Third man to set foot on the moon, 19 Nov. 1969.

Scientist-pilot: Comdr. Joseph P. Kerwin, MC, USN. Born 19 Feb. 1932 in Oak Park, Ill. B.A. in philosophy, College of the Holy Cross, Worcester, Mass., 1953; M.D., Northwestern University Medical School, 1957. Commissioned in Navy Medical Corps 1958; qualified as pilot 1962. Joined NASA in 1965 with the first group of scientist-astronauts (4th group selected). No spaceflight experience prior to Skylab.

Pilot: Comdr. Paul J. Weitz, USN. Born 25 July 1932 in Erie, Pa. B.S. in aeronautical engineering, Pennsylvania State University, 1954; M.S., U.S. Naval Postgraduate School, 1964. Commissioned 1954, qualified as pilot 1956. Served six months on U.S.S. *Independence,* earning the Air Medal with four stars, the Navy Commendation Medal, and the Navy Unit Citation. Selected as an astronaut in 1966 with the fifth group of astronauts. No spaceflight experience prior to Skylab.

2d Crew

Commander: Capt. Alan L. Bean, USN. Born 15 March 1932 in Wheeler, Tex. B.S. in aeronautical engineering, University of Texas (Austin), 1954. Commissioned from NROTC on graduation; qualified as a pilot and completed the Navy Test Pilot School. Joined NASA in 1963 with the third group of astronauts. After backup assignments on *Gemini 10* and *Apollo 9,* he was lunar-module pilot on *Apollo 12* and was the fourth man to walk on the moon, 19 Nov. 1969.

Scientist-pilot: Owen K. Garriott (civilian). Born 22 November 1930 in Enid, Okla. B.S. in electrical engineering, University of Oklahoma, 1953; M.S. and Ph.D. in electrical engineering, Stanford University, 1957, 1960. Taught and conducted research at Stanford until 1965; selected as an astronaut in 1965 with the first group of scientist-astronauts. No spaceflight experience prior to Skylab.

Pilot: Maj. Jack R. Lousma, USMC. Born 22 August 1932 in Grand Rapids, Mich. B.S. in aeronautical engineering, University of Michigan, 1959. Commissioned in 1959; qualified as a pilot in 1960. Joined NASA with the fifth group of astronauts in 1966. No spaceflight experience prior to Skylab.

3d Crew

Commander: Lt. Col. Gerald P. Carr, USMC. Born 22 August 1932 in Denver. B.S. in mechanical engineering, University of Southern California, 1954. Commissioned from NROTC on graduation, he qualified as a pilot and served as a fighter pilot with Marine squadrons overseas from 1962 to 1965. Joined NASA with the fifth group of astronauts in 1966. No spaceflight experience prior to Skylab.

Scientist-pilot: Edward G. Gibson (civilian). Born 8 November 1936 in Buffalo, N.Y. B.S. in engineering, University of Rochester, 1959; M.S. in engineering, Ph.D. in physics, California Institute of Technology, 1960, 1964. Senior research scientist in the Applied Research Laboratories of the Philco Corp. until selected as an astronaut in 1965 with the first group of scientist-astronauts. No spaceflight experience before Skylab.

Pilot: Lt. Col. William R. Pogue, USAF. Born 23 January 1930 in Okemah, Okla. B.S. in education, Oklahoma Baptist University, 1951; M.S. in mathematics, Oklahoma State University, 1960. Commissioned in 1952, flew 43 combat missions in Korea, earning the Air Medal and the Air Force Commendation Medal. Member of the USAF Thunderbirds, 1955–1957. Taught mathematics at the Air Force Academy, 1960–1963. Graduated from the RAF Empire Test Pilots' School and served two years as a test pilot with the British Ministry of Aviation. Joined NASA in 1966 with the fifth group of astronauts selected. No spaceflight experience prior to Skylab.

Backup for 1st Crew

Commander: Russell L. Schweickart (civilian). Born 25 October 1935 in Neptune, N.J. B.S. and M.S. in aeronautical engineering, Massachusetts Institute of Technology, 1956, 1963. Conducted research in upper atmosphere physics at the Experimental Astronomy Laboratory at MIT before joining NASA with the third group of astronauts in 1963. Served as lunar-module pilot on *Apollo 9*, 3–13 March 1969, testing extravehicular activity procedures and simulating a lunar-orbit rendezvous with the command module.

Scientist-pilot: F. Story Musgrave (civilian). Born 19 August 1935 in Boston. B.S. in statistics from Syracuse University, 1958; M.B.A. in operations analysis from University of California at Los Angeles, 1959; B.A. in chemistry from Marietta College, 1960; M.D. from Columbia Medical School, 1964; M.S. in biophysics from the University of Kentucky, 1966; studied physiology at University of Kentucky. Selected with the second group of scientist-astronauts in 1967. No spaceflight experience.

Pilot: Lt. Comdr. Bruce McCandless II, USN. Born 8 June 1937 in Boston. B.S. from U.S. Naval Academy, 1958; M.S. in electrical engineering, Stanford University, 1965. Qualified as a pilot in 1960 and served on board U.S.S. *Forrestal* and U.S.S. *Enterprise*, 1960–1964. Joined NASA with the fifth group of astronauts in 1966. No spaceflight experience.

Backup for 2d and 3d Crews

Commander: Vance D. Brand (civilian). Born 9 May 1931 in Longmont, Colo. B.S. in business, University of Colorado, 1953; B.S. in aeronautical engineering, 1960; M.B.A. from UCLA, 1964. Pilot, Marine Corps, 1953–1957; test engineer with Lockheed Aircraft Corporation, 1960–1966. Graduated from U.S. Naval Test Pilot School, 1963, and served as experimental test pilot and leader of a Lockheed advisory group with the West German Air Force. No spaceflight experience prior to Skylab; later flew as pilot on the Apollo-Soyuz Test Project mission, 15–24 July 1975.

Scientist-pilot: William B. Lenoir (civilian). Born 14 March 1939 in Miami, Florida. B.S., M.S., and Ph.D. in electrical engineering, MIT, 1961, 1962, 1965. Taught and conducted research at MIT, 1964–1967. Joined NASA with the second group of scientist-astronauts in 1967. No spaceflight experience.

Pilot: Don L. Lind (civilian). Born 18 May 1930 in Midvale, Utah. B.S. in physics, University of Utah, 1953; Ph.D. in high energy physics, University of California (Berkeley), 1964. Conducted experiments on low-energy particles in the earth's magnetosphere at Goddard Space Flight Center, 1964–1966. Qualified as a Navy pilot in 1955 and served two years active duty before joining NASA in 1966 with the fifth group of astronauts.

SOURCE: House Committee on Science and Technology, *Astronauts and Cosmonauts: Biographical and Statistical Data*, report prepared by the Science Policy Research Div., Congressional Research Service, Library of Congress, 94th Cong., 1st sess., June 1975; NASA Hq., "Skylab News Reference," March 1973.

Appendix F
Comet Kohoutek

NASA'S OBSERVATIONS OF COMET KOHOUTEK

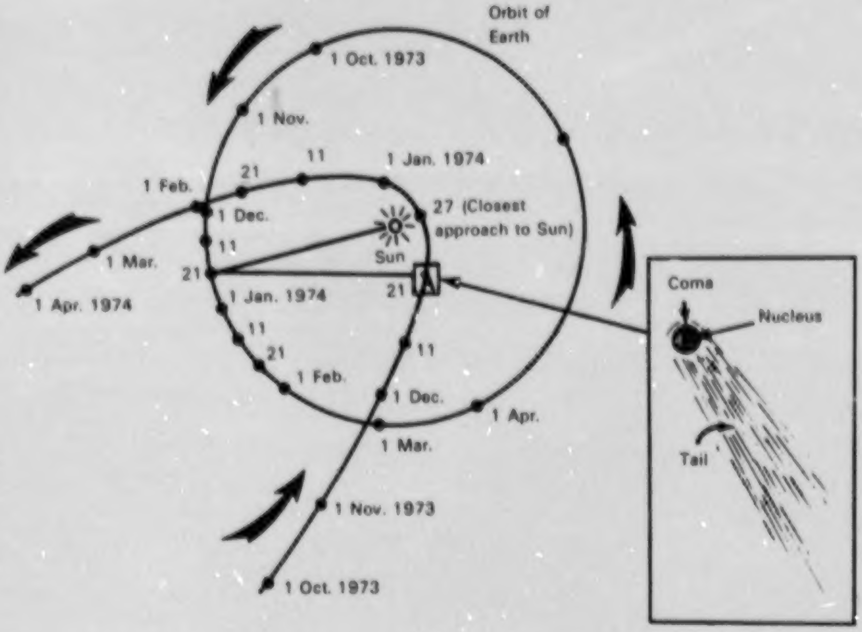
Comet 1973f, discovered by and named for Lubos Kohoutek, was an exception to the general experience with comets. It was discovered farther from the sun (73.9 million km) and earlier (7 months before perihelion) than any previously reported comet; early calculations of its path showed that it would swing inside the orbit of Mercury; and its brightness when discovered indicated that it was exceptionally large. Its size and near approach to the sun indicated that it would be extraordinarily brilliant when it passed perihelion in late December 1973.[1]

Presented with eight months of lead time, astronomers around the world began planning extensive and systematic observations. NASA prepared to use all its available instruments to contribute to this worldwide program. Some astronomers working on other NASA-sponsored projects diverted part of their resources to comet observations; a few special grants were awarded; other experimenters worked on instruments to be flown in aircraft or sounding rockets. A special "Operation Kohoutek" office was established at Goddard Space Flight Center to coordinate NASA's observations; it also coordinated activities with the Smithsonian Observatory, Kitt Peak National Observatory, and the National Radio Astronomy Observatory. Existing instruments constituted the bulwark of NASA's program, even though all of them were designed for other purposes. *Mariner 10,* launched toward Mercury on 3 November 1973; *Orbiting Solar Observatory 7,* in orbit since September 1971; and Skylab's Apollo telescope mount were the principal ones. A new Joint Observatory for Cometary Research near Socorro, New Mexico, not yet formally dedicated, was brought into operation for Kohoutek.

As 1973 progressed, earlier predictions of the comet's size and brightness were modified downward by further observation. Astronomers were not surprised, as comets are probably the least understood and least predictable of celestial objects, but certain of the planned observations had to be altered. The rest were carried out very much as planned, with gratifying results.

Preliminary examination of those results showed Kohoutek to have been a most interesting comet. Spectroscopic evidence for water in a comet was obtained for the first time, supporting a widely accepted theory that comets consist largely of ice and frozen gases. Another interesting discovery was Kohoutek's emission of radio frequency radiation identified with the polyatomic molecules hydrogen cyanide and methyl cyanide. Both of these molecules have been detected in intergalactic space, but never before in comets. The observation lends credence to the supposition that comets are composed of the primordial material out of which the solar system was formed.

Kohoutek was also unique in being apparently a "new" comet, one that had never before passed the sun. This at least was offered as an explanation for its considerably diminished brightness after perihelion. Never having been heated before, it contained much more volatile material than periodic comets. This material boiled off during approach to the sun, releasing some of the solid particles embedded in it and creating a large cloud of highly reflective dust. But by the time the comet rounded the sun and became favorably placed for observation from earth, it had diminished in size and brightness much more than an older comet would have.



Orbit of Comet Kohoutek, 1973–1974.

Skylab's observations of comet Kohoutek were a small part of the total study, but they were among the important ones. The photometric images taken daily from the workshop's orbit above the atmosphere provided a good record of the comet's intrinsic brightness. The crew's visual observations and color sketches were far better than any such made from the ground. Integrated into the rest of the studies made around the world, they will eventually play a part in understanding what comets are and where they come from.

KOHOUTEK AS A MEDIA EVENT

Kohoutek's early discovery and the busy preparations to study it were scientifically noteworthy, but—one might suppose—hardly the stuff to excite the press generally. Other comets had come and gone in recent years without drawing newspaper attention. But the coincidence of its perihelion with the Christmas season, the early predictions that it would be the most spectacular celestial display since Halley's comet in 1910, and the involvement of a manned spaceflight, combined to make it newsworthy. Over the last six months of 1973 American newspapers—ably assisted by an intensive public relations campaign by NASA—gave more coverage to its approach than to any such exotic event within memory.[2]

In July 1973 a Washington paper reported that NASA was considering delaying the launch of the third Skylab crew by two to three weeks in order to have the solar instruments manned as comet Kohoutek swung around the sun. Associate Administrator for Manned Space Flight Dale D. Myers remarked that while such a delay would be expensive, "comets this size come this close once in a century. It really looks like the kind of thing you can't pass up."[3] A few weeks later the preparations being made at NASA's Ames Research Center at Moffett Field, California, attracted the attention of a San Jose reporter, who noted "the excitement bubbling among the ranks of researchers who are accustomed to deliberate, carefully qualified phrases." They were, he said, calling it "the comet of the century."[4]

Very quickly this phrase became ineluctably attached to the new comet. Preliminary estimates that it would be larger and brighter than Halley's comet, even that it might be visible in midday, were given wide currency. A magazine for serious amateur astronomers warned, "Just how bright the comet will become cannot yet be forecast reliably,"[5] but from 16 August, when NASA announced postponement of the Skylab launch to allow observation of the comet, most of the press ignored such negativism.[6]

As the launch of the last Skylab mission approached, more comet stories, still featuring the earliest estimates of size and brightness, appeared. An Associated Press release, quoting NASA scientists, promised the most spectacular celestial sight in more than a century, reiterating the comparison with Halley's comet. Kohoutek might be as bright as the full moon, with a tail stretching across a sixth of the sky, according to another report. Again, for more knowledgeable readers, NASA's director of Operation Kohoutek, Stephen Maran, cautioned that comets are highly unpredictable; Kohoutek could split or even disappear as it drew closer to the sun.[7]

Through November the comet was still invisible to the unaided eye, but public interest intensified. A three-day cruise aboard the luxury liner *Queen Elizabeth II* was almost fully booked early in the month; by December, 1693 people had paid $130 to $295 each to sail out into the Atlantic, hoping to find dark and clear skies to glimpse the comet just before dawn. A leading marketer of telescopes for amateurs reported sales up by 200%. Eastman Kodak company published a booklet containing tips for photographing the yet-unseen spectacle. By now, however, skeptical notes were creeping into some accounts. While *Newsweek* was reporting that "astronomers are predicting that comet Kohoutek will prove an even more spellbinding spectacle than Halley's comet," the *New York Times* hedged: "some astronomers fear that the comet has been 'oversold' and will be a disappointment to many." An official of the Brevard County, Florida, astronomical society offered the opinion that Kohoutek would not be "the comet of the century. . . . I don't think it will be seen in the middle of the day." By late November it was reported that already there were signs that "the first predictions of post-Christmas brilliance may have been overoptimistic."[8]

That was not enough to still the frenzy that had been built up by most papers, however. Feature writers had a field day recalling the history of spectacular comets and the superstitions associated with them. Planetariums across the country staged comet shows, and here and there installed special "comet hot-lines" providing recorded information by telephone. And although by early December only a few astronomers and well equipped hobbyists had seen Kohoutek, the spate of stories did not abate, for as the comet approached perihelion it would surely begin living up to expectations.[9]

Those who sailed on the *QE2*, as it turned out, had to get their money's worth out of entertainment other than the comet—which, probably, many of them had planned to do anyway. Clouds covered the area much of the time and the sea was not kind: many of the passengers got seasick. Lubos Kohoutek, who was brought along as one of the featured attractions of the cruise, thought he caught a glimpse of the comet in the predawn darkness, but he was not sure. In the midwest, the early December weather foiled most of those who tried to get a look at comet Kohoutek. The *New York Times* reported that even those who could see it were likely to feel let down: "the much-publicized Comet Kohoutek is proving a disappointment to astronomers, if not a fizzle." Only three days before, NASA's spokesman for Operation Kohoutek had reiterated that the comet could be "the greatest fiery chariot of all time."[10]

NASA's promotion of the still-invisible comet was producing excellent results when the third Skylab crew was launched—so good, in fact, that the White House made a tentative attempt to ride the comet's coattails. An adviser to the Domestic Council approached NASA Administrator James C. Fletcher proposing a half-hour television special linking comet Kohoutek, Skylab, and the first family's Christmas message to the country. Six months earlier this same adviser had urged the council to exploit the space program and its benefits for the benefit of the president's image. He argued that the "Flash Gordon" side of space ventures had been neglected. Comparing the coverage of spaceflight with the film *2001: A Space Odyssey* and the television series *Star Trek*, he found it unimaginative, boring, and unappealing, and suggested that what was needed was to "really sock space to the American people for the first time in a way they have wanted it all along." Against that background, NASA's Assistant Administrator for Public Affairs John P. Donnelly reacted adversely to the television proposal, finding it neither imaginative, perceptive, nor incisive. Donnelly pointed out that involving NASA in politics—as the suggestion was sure to do—would be a very bad thing for the space program. (He did not need to say that it was a highly inopportune time to entangle the space agency with the fortunes of Richard M. Nixon while the Watergate investigations were uncovering damaging evidence against the president and his advisers.) Although the White House proposal was the subject of high-level and highly charged discussions within NASA, Donnelly's view prevailed.[11]

The comet could have done the president no good, as events turned out; the hazards of predicting comet behavior came home to astronomers and journalists alike in the next month. Over a period of three weeks Operation Kohoutek director Stephen Maran revised his pronouncements drastically. On 20 December he called early predictions of its brightness "optimistic" in view of current opinion that Kohoutek was a new comet. A week later he said it was "*not* the comet [of the century] from the point of view of public viewing." Scientifically it would be very important, but "it won't be as spectacular as we had hoped." When a reporter asked about the 160-million-kilometer tail that was supposed to stretch across a sixth of the sky, Maran said that estimate was "outdated."[12]

Early in the new year newspapers were wondering what had become of the brilliant spectacle they had been touting for six months. Serious amateurs and professional astronomers obtained many valuable and beautiful photographs of the comet, but the general public was disappointed, to say the least. Reporting that the comet was about as bright as the average star, one paper headlined its story, "Kohoutek: The Flop of the Century?" No expert would venture a confident opinion as to the cause. By 10 January 1974 Kohoutek was visible only through binoculars. A spokesman for Goddard Space Flight Center acknowledged that "from a public relations point of view, it has been a disaster," though he insisted that "from a scientific point of view, it has been a roaring success." A story in the *Philadelphia Inquirer* summed up the press view succinctly: "The 'Comet of the Century' Went Phzzzt."[13]

With the comet sailing off into space, perhaps on a hyperbolic path that would never bring it back, serious reporting gave way to parody and satirical comment. A guest columnist for the *Chicago Tribune* broadly spoofed the astronomical debacle by attributing the pre-perihelion predictions to a government plot to take the public's mind off the unfolding Watergate scandals, or a conspiracy with the telescope industry to boost sales. In the *New York Times* Russell Baker wrote lightly of "The Cosmic Flopperoo," while Art Buchwald interviewed a fictitious comet dealer who pointed out that his product was not warranted against failure to shine.[14] The Kohoutek binge was over.

Press treatment of comet Kohoutek had emphasized the spectacular possibilities. Perhaps reporters, encouraged by scientists' understandable enthusiasm for a major comet's appearance just when it could effectively be studied, overlooked the fact that comets are notoriously unpredictable. Kohoutek's unparalleled early discovery allowed much more time for both scientific preparation and public attention—which few comets get. Perhaps some writers, noting that comets had traditionally heralded the fall of princes and other dire events, saw some connection between Kohoutek and Watergate. And no doubt the coincidence of the comet's passage around the sun with the Christmas season added interest.

Mostly, however, the press simply bamboozled itself, ignoring the cautions occasionally invoked by the astronomers. Kohoutek had been treated as a sure thing from the beginning, and when it misfired, the press felt victimized. None of it, of course, was really necessary. In its March 1974 issue, *Sky and Telescope*—which had calmly published the sober facts about Kohoutek—reflected on the press's overreaction:

> The impression made by Comet Kohoutek 1973f depends very much on with whom you talk. Professional astronomers are enthusiastic about the observations they obtained that should tell much about the structure and origins of comets. Knowledgeable amateurs were rewarded by a beautiful and delicate object in the evening sky, better seen with binoculars than with the naked eye, and difficult to photograph. But the general public wondered what had happened to the spectacle promised by the news media.
>
> Actually, 1973f was a large comet comparable to 1970 II (Bennett), and any disappointment was mainly due to overenthusiastic advance publicity.[15]

Appendix G
Joint Observing Program 2, Active Regions

RESEARCH OBJECTIVES

Study the three dimensional structure of active regions, the horizontal and vertical variation of the temperature, density, velocity, and magnetic field.

Study the short term (minutes to hours) and long term (days) evolution of the chromosphere, transition region, and corona in active regions.

Investigate the relationship between the three dimensional structure of an active region and its evolution as it relates to the production of flares and other transient phenomena.

Obtain information about the structure of the photosphere, chromosphere, transition region, and corona in and above sunspots.

Map the differential velocity fields in the chromospheric, transition, and coronal layers over active regions and other solar features.

OBSERVATIONS

X-ray filtergrams from S054 and S056 and spectroheliograms from S055 and S082A will contain information about the three dimensional structure. In addition, the spectra obtained by S055 and S082B will contain detailed information about the variation of temperature, density, and velocity with height at selected positions. White light pictures of the corona from S052 will provide a detailed description of the density structure of the corona overlying active regions. For evolutionary studies, observations will be obtained at a rate compatible with the time scale of the development of the regions.

OPERATIONAL DESCRIPTION

A. Rapidly developing active region: This program will be initiated when the astronaut or PIs observe a rapidly developing active region. When the decision is made to carry out this observation, BB-5 [building block 5, a set of instructions for setting up the instruments] will immediately be carried out. BB-5, BB-6, and/or BB-10 may be repeated a number of times as determined by the PIs. If the active region is within 45° of the limb, BB-2 should be carried out as often as determined by the PIs. Which building blocks are performed will depend on the rate of development of the active region and/or the flaring rate of the region.

B. Long-term evolution of an active region: The active region to be studied will be selected by the PIs on the ground and pointing information will be telemetered to the astronauts. An active region will be selected that can be studied for a minimum of 10 days and at least one limb passage. The most desirable observation would be from limb to limb.
   1. When the active region is on the disk, it should be observed once per day, performing BB-4 and BB-5 on alternate days. Point ATM at different bright and

dark areas of the plage. For the S055 spectra, the pointing should be adjusted so that output of detector no. 3 (grating in optical reference) is maximized for some points and minimized for some points. When the active region is within 45° of the limb BB-2 will be carried out at least once.

2. When the active region is near the limb passage BB-2 (once) will be carried out, followed by BB-5 (once), BB-6 (3 times), BB-13 (once), BB-14 (once), and BB-2 (once).

C. Structure of active regions: The active region to be studied will be selected by the PIs on the ground. The ATM slit will be pointed at a number of selected positions across the active region, and BB-6, and/or BB-5, and/or BB-4, will be performed, with the number of times in each mode being selected during the mission.

D. Sunspots: An active region containing large sunspots will be selected for study. If the diameter of the umbra is at least 60 arc seconds, the ATM slit will be pointed at two positions in the center of the umbra, and BB-6 plus BB-12 will be carried out (2 pointings). ATM will also be pointed at two positions in the penumbra, and BB-6 plus BB-12 performed at each point. If the diameter of the umbra is significantly less than 60 arc seconds, the above sequences may be performed without S082B.

E. Chromospheric velocities: This program will be implemented in the following manner. An active region or other area of interest will be selected. The ATM slit will be pointed at the area, rolled so that the S055 scan line is east-west, and BB-18 carried out. The ATM will be rolled 90°, so that the S082B slit is parallel to the S055 scan line in BB-18, and positioned along that line to the best position for observing uniform line-of-sight plasma motion. BB-11 will then be performed. S055 and S082B will obtain velocity information while S054, S056, and S082B obtain information about the atmospheric structure in the region being observed.

Source Notes

In preparing this history the authors were granted access to NASA documents at several sites. A large collection (occupying some 15 linear meters of shelf space) had already been compiled by Roland Newkirk and Ivan Ertel for the preparation of *Skylab: A Chronology* (NASA SP-4011, Washington, 1977). To this collection, which was housed in the History Office at Johnson Space Center, we added documents from several other sources: the archives at Kennedy Space Center (now a part of that center's technical library), the History Office at NASA Headquarters, the reading files from the Skylab offices at JSC, and the records of the various project offices at Marshall Space Flight Center. Most of the Marshall documentation has been retired to the Federal Records Center at East Point, Ga.; it can be recalled through the Management Operations Office at Marshall.

One valuable source at Marshall was the collection of Leland F. Belew, some 50 cartons of documents accumulated during his eight years as Skylab program manager. We were also allowed to screen and copy the weekly notes submitted to Marshall's director by each laboratory director and major project manager; these, though brief, document important milestones and the general progress of the program, and often contain handwritten notations by the director—queries, suggestions, or comments that are of value. Similarly we screened and copied the minutes of Marshall's staff and board meetings.

The volume of available documentation on Skylab is staggering. For example, the authors screened 57 cartons (about 2.5 cubic meters) of files from the orbital workshop project manager at Marshall—which was only a selected part of the total files. Each of the other Skylab modules produced comparable quantities of paper. The files at the other centers, though somewhat less voluminous, are equally detailed. The researcher who digs into this midden will find material on the most minute engineering and management details, as well as higher-level technical and management decisions. From this mass of paper we selected and copied the documents used in writing this history.

The Skylab archives now comprise copies of official correspondence, technical manuals, flight plans, technical debriefings of crews, and transcripts of all communications during flight; news reference material and press conferences; and transcripts of interviews we conducted with more than 60 program participants. The collection occupies 88 cartons.

In January 1982 these documents, along with those from the Mercury, Gemini, and Apollo-Soyuz Test Project programs, were transferred from the JSC History Office to the custody of the Fondren Library at William Marsh Rice University in Houston. A custodial agreement between Rice and JSC provides for these documents to be stored, archived, and indexed at the Fondren Library and made available to researchers interested in the development of manned spaceflight. JSC retains title to the documents.

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Chapter 14

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Chapter 16

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are in Onboard. The transcript made by the JSC Public Affairs Office attributes "between you, me, and the couch" to Pogue and the final quote to Carr. We did not listen to the tapes to attempt to settle the matter. For one other discrepancy between these transcripts, see n. 48. Gibson, interviewed 5 July 1977, recalled that he and Carr could imagine the consternation Pogue's illness would cause and the delay their mission would suffer as a result of the doctors' determination to do something about it. In view of their desire to get on with the mission, they concluded that their best course was to save the bag, process it, and report the affair after the mission was over—assuming that Pogue had recovered by the morning of 17 November. None of this, however, is reflected in the transcripts of tapes from the onboard recorder. A memo filed with the flight director's handover notes (prepared by each retiring flight director for his relief) records that the astronauts' "feeling of undue concern about what reactions the report of the emesis would generate resulted in the report delay. The emesis was saved contrary to earlier deliberations to dismiss the significance of the emesis." Jerry R. Hordinsky, "Mission Surgeon's Daily Report on Crew Health," 17 Nov. 1973. Later that day, the flight director (Neil Hutchinson) of the Silver team noted the discovery of the incident in the channel B transcripts, commenting that the crew "have been chastized [*sic*] at privacomm med [private communication, medical] & I get to tell the press about the entire incident tonight." Unsigned, undated notes, "Handover, Silver [to] Bronze," in "Skylab Flight Directors' Handover Notes, Day 316 to 340," from JSC Flight Operations Directorate.

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Appendix F

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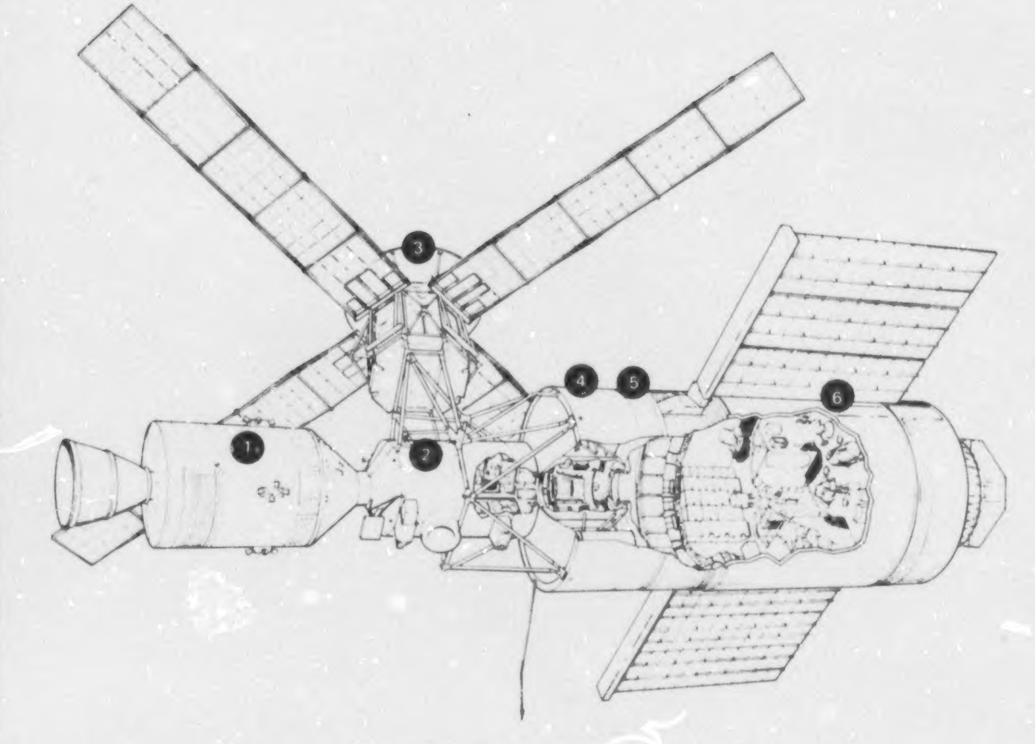

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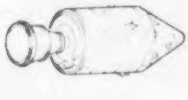
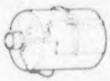
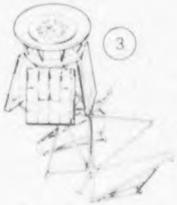
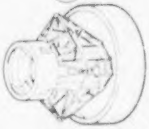
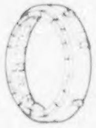
① 	Apollo Command and Service Module	Crew Ascent & Descent	10.5	3.9	10.4
② 	Multiple Docking Adapter	Docking Telescope & Earth-Resource Controls & Displays	5.3	3.1	32.3
③ 	Apollo Telescope Mount	Solar Observation	4.1	—	—
④ 	Airlock Module & Fixed Shroud	Power Control & Distribution Environmental Control Utility Center Data System Extravehicular Activity Port	5.4	3.1	17.3
⑤ 	Instrument Unit	Launch Vehicle Control	0.9	6.6	—
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